APPLICATION OF MoS_2 BASED CUTTING FLUIDS IN MINIMUM QUANTITY LUBRICATION DURING MACHINING OF STAINLESS STEEL AISI 316L

Thesis Submitted in Partial Fulfillment
of the Requirements for the Award of

Master of Technology

In

Production Engineering

By

S Anandita

Roll No: 212ME2289

Department of Mechanical Engineering, National Institute of Technology Rourkela

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M.Tech Thesis

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Under the Guidance of

Prof. S.Gangopadhyay

Department of Mechanical Engineering
National Institute of Technology
Rourkela

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National Institute Of Technology, Rourkela

CERTIFICATE

This is to certify that the thesis entitled, **"Application of MoS_2 based cutting fluids in minimum quantity lubrication during machining of stainless steel AISI 316L"** submitted by **Ms. S Anandita** in partial fulfillment of requirements for the award of Degree of Master of Technology in **Mechanical Engineering** with specialization in **"Production Engineering"** at National Institute of Technology, Rourkela is an authentic work carried out by her under my guidance and supervision. To the best of my knowledge the matter embodied in the thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

Date: 01-06-2014

Dr. S. Gangopadhyay
Assistant Professor,
Department of Mechanical Engineering,
National Institute of Technology
Rourkela- 769008

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S Anandita

Roll No.212 ME 2289,

Department of Mechanical Engineering,

National Institute of Technology

Rourkela- 769008

ABSTRACT

Last decade witnessed rapid increase in development of advanced materials for high performance applications. While these materials solve a great deal of technological issue, they also pose considerable challenge in machining due to poor machinability characteristics. Many strategies have been devised. However, environmental friendly machining techniques have been given major emphasis and minimum quantity lubrication (MQL) technique is one of them. Although molybdenum disulfide (MoS_2) is widely regarded as solid lubricant material, its potential as an effective medium in MQL particularly in turning operation is yet to be explored. During the current research work, the effect of addition of MoS_2 powder, with average size of around 1 µm, in two different base fluids namely conventional water soluble oil and paraffin oil (a mineral oil) has been investigated during turning of AISI 316L grade austenitic stainless steel with the help response surface methodology (RSM)-based design of experiment. The results clearly indicated the beneficial aspects of MoS_2 in reducing the cutting temperature by virtue of enhanced heat transfer characteristics of micro-particle of MoS_2.The same powder also helped in bringing down cutting force and chip thickness while improving surface finish. It was observed that MoS_2-mixed conventional cutting fluid demonstrated superior machining characteristics. Further attempt was also made to determine optimal cutting condition using grey relational analysis (GRA)-based multi objective optimization technique. The study, therefore, clearly established promising potential of MoS_2 powder to be mixed with suitable base fluid under MQL environment during machining AISI 316L grade austenitic stainless steel.

***Keywords**: Minimum quantity lubrication, molybdenum disulfide, conventional water soluble cutting oil, paraffin oil, machining, AISI 316L stainless steel.*

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CHAPTER 1

INTRODUCTION

1.1 Machining

Machining is one of the most critical processes in the manufacturing industries which involve a controlled removal of material from the substrate by using a cutting tool. Since machining involves plastic deformation of the workpiece material and friction between tool-chip and tool-workpiece interfaces, lot of energy supplied is converted into heat. During the machining of low strength alloys, this heat generation is less but when ferrous and other high strength alloys are machined, lot of heat is generated which increases with a subsequent increase in the cutting speed. The distribution of heat generated during machining is shown in Fig. 1.1.This heat generated, if not dissipated successfully, may affect the finished surface quality, reduce the tool life and hence overall performance of the process. Thus, although high speed machining is desirable in many cases for higher productivity, the consequences of heat generation needs to be minimized.

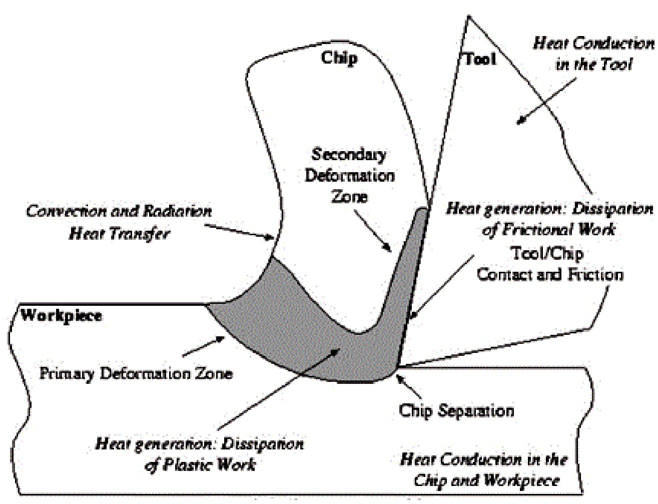


Fig. 1.1: Generation and distribution of heat during machining [1]

Many techniques were evolved for the effective removal of heat from the vicinity of the machining area. One of those techniques is applying coolant in the form of fluid during the process.

For many years, coolants, popularly known as metal working fluids (MWF) continued to be successfully employed for the heat removal until it was realized that these fluids are a serious damage to the environment and to the health of the operator working with it. The researches of Klocke and Eisenblatter (1997b) showed that they create a waste disposal problem and add to the cost of the manufacturing. These negative consequences of the flood cooling promoted the researchers to switch to those technologies which involve least usage of the cutting fluids [2].

Many alternatives were developed to minimize the quantity of cutting fluid used. Some such techniques that came into focus were:

- Dry machining
- Cryogenic cooling
- Coated tools
- Minimum quantity lubrication

1.1.1 Dry machining

In order to avoid the use of cutting fluids because of their harmful ecological and health effects, machining in many cases is carried out without using any cutting fluid. This is possible only at low cutting speeds and easily machinable materials. Generally, dry machining is not suitable in cases where excellent surface finish and high dimensional stability are required. This is so because dry machining involves high temperature generation which enhances the formation of built up layer. This built up layer due to its unstable nature breaks and takes away a portion of tool material due to its high adhesive nature causing tool wear. The broken segments when stick to the machined surface deteriorates the surface finish. Thus, dry machining without any lubricating and cooling enhancement is not preferred in general cases of machining.

1.1.2 Cryogenic cooling

Cryogenics is defined as working with materials at temperatures less than -150ºC (123K). Mostly liquid nitrogen is used as the cryogen material. It is a colorless, odorless and a non toxic gas. It constitutes about four-fifth of the atmospheric gases. Its boiling point -198.79ºC and melting point is -210.01ºC. These characteristics make liquid nitrogen (LN_2) as the most suitable gas for the cryogenics applications [3]. During machining, the cryogenic coolant is supplied to the machining area (cutting zone) where heat generation is prone to be maximum. The coolant absorbs heat and lowers down the maximum temperature reached thus contributing in tool life enhancement.

1.1.3 Coated tools

In order to avoid the usage of cutting fluids during machining processes, nowadays coated tools are gaining popularity. In this method the tool inserts are provided with a coating which can serve the following purposes.

1. It should have low thermal conductivity so that it does not allow any heat to enter into the bulk material of the tool.
2. It should have good resistance to abrasion wear and must possess high thermal and chemical stability.
3. It must possess low friction coefficient and must be securely bonded to the tool substrate material.

Most commonly used coating materials are titanium based coating materials such as TiAlN, TiN, TiAlCrN etc.

1.1.4 Minimum quantity lubrication

The main aim of minimum quantity lubrication (MQL) is to reap the benefits of cutting fluids without getting affected with the harmful effects of the cutting fluids. It involves the usage of minimal quantity of cutting fluid with a typical flow rate of 50-500 ml/h which is directly applied to the cutting zone thereby avoiding the need of fluid disposal as it happens in flood cooling. Since MQL involves significantly lesser amount of cutting fluid, this phenomenon is popularly referred to as ‘near dry machining’ or ‘micro lubrication’ or ‘spatter lubrication’[2].

Methodology

This method involves the application of an aerosol of highly compressed air (typical pressure of air = 4-6 bar) and cutting fluid (lubricant) through a specially designed nozzle with hole diameter of magnitude 1-2mm. In this method, as the cutting fluid in the form of small droplets of aerosol comes in contact with the heated cutting zone, it evaporates extracting the latent heat from the machining area. Thus, this method involves removal of heat by evaporative transfer rather than convective heat transfer method. Since, evaporative heat transfer method is more efficient in terms of extracting heat and also there is no waste disposal problem, MQL surely has an extra advantage with respect to conventional flood cooling.

There are two methods of mixing air and lubricant in MQL method.

1. Mixing inside the nozzle
2. Mixing outside the nozzle

In the first method, the lubricant and air is mixed just before reaching the nozzle in a mixing chamber. The oil-mist is then supplied through the nozzle at high pressure onto the cutting zone. The oil performs the lubricating function while highly pressurized compressed air performs the cooling action.

In the second method, the mixing of oil and compressed air is done in a separate mixing chamber.

Advantages of minimum quantity lubrication

Minimum quantity lubrication technique offers several advantages over conventional flood cooling which can be summarized as below:

- It involves comparatively very less amount of cutting fluid thus making this process almost dry and clean.
- The oil mist droplets quickly vaporize away taking away the heat along with them making this process clean and environmentally friendly and healthy for the workers.
- It involves the usage of both the cutting fluid and highly compressed air, thus the responsibility of cooling and lubrication is shared between the compressed air and the cutting fluid. On one hand, the cutting fluid provides the lubricating effect while the highly pressurized air fulfils the task of cooling the machining zone.
- The mixture of highly pressurized air and cutting fluid flushes away the chip more efficiently thus making chip disposal a much easier task.
- The machining processes performed with minimum quantity lubrication have proved to be more productive, with an increased tool life and better surface finish.

Applications of minimum quantity lubrication

Minimum quantity lubrication is widely applicable in different machining operations such as turning, drilling, milling, grinding etc.

1.2 Cutting fluids

Cutting fluids are widely used in machining operations to serve the purpose of reducing thermal deformation by cooling the machining zone and improving the surface finish by providing good lubrication. The main functions of cutting fluids can be summarized as below:

- Cutting fluids serve the purpose of cooling the extremely heated cutting zone by taking away some of the heat generated.
- They reduce the coefficient of friction between the tool-chip and tool-workpiece interfaces so as to lower down the heat generated due to frictional effect, thus, lubricating the surfaces.
- They serve the purpose of reducing the tendency of thermal distortion by lowering down the thermal gradient.
- They flush away the chips from the machining zone thereby facilitating the disposal of chips.
- They protect the finished workpiece surface from corrosion and rust fromation.

1.2.1 Properties of cutting fluids

The cutting fluids which are to be used must possess the following essential properties which contribute in making them apt for fulfilling their functions.

- A good cutting fluid must have large specific heat capacity and good thermal conductivity.
- It should have low viscosity.
- It should be non toxic, non corrosive and should not react with the tool or workpiece material.
- It should not be very costly and should be easily available.

- It should have high flash point.
- It should be physically and chemically stable.

1.2.2 Types of cutting fluids

There are two broad categories into which cutting fluids may be classified:

- Water miscible cutting fluids
- Mineral oil based cutting fluids

Water miscible fluids

Water miscible cutting fluids are those cutting fluids which contain water as the main base fluid. Water is a fluid which has got excellent cooling property. Thus water miscible cutting fluids have good heat absorbing characteristics.

Water miscible fluids consist of water soluble oils mixed with water. These water soluble oils are generally emulsifiers (soap like substance). These oils when mixed with water in a small quantity produce a milky white material which is then supplied to the cutting area.

Mineral oil based cutting fluids

These oils do not get mixed with water. They can be used as mixtures of mineral or vegetable oils. Several additive compounds such as sulphur, phosphorous, chlorine based components can be added to the base cutting fluids in order to improve their cooling and lubricating properties.

1.3 Nano lubrication

Nano lubrication can be defined as the process of cooling and lubricating the cutting zone during any machining operation by employing nanofluid instead of the normally used cutting fluids.

1.3.1 Nanofluids

Nanofluids are prepared by mixing a specific amount of nnaoparticles (having size of the order of few nanometers) into the cutting fluid. The nanoparticles on account of their different specific densities may have the tendency to settle down or float depending upon the cutting fluid used. Thus, the nanoparticles are mixed thoroughly into the cutting fluid by using an ultrasonic vibrator for approximately 48 hours.

Nanoparticles, on account of their very small size have got high surface area to volume ratio. Due to their large surface area, their heat dissipating capacity increases to a great extent. Thus, nanoparticles have got excellent heat dissipating characteristics. Different types of nanoparticles can be used to enhance the cooling and lubricating properties of the cutting fluids. Some of the nanoparticles that can be employed in the cutting fluids for cooling and lubricating purposes are:

- Molybdenum disulfide nanoparticles
- Aluminium oxide nanoparticles
- Graphite nanoparicles
- Carbon nanotubes
- Silver nanoparticles etc.

CHAPTER 2

LITERATURE REVIEW

2.1 Minimum Quantity Lubrication

The continuous increasing demands in modern industries have led to a need of high material removal rate, dimensional accuracy and high surface finish. The high production requirements in the metal removal processes are met by incorporating high cutting velocity, depth of cut and tool feed. This leads to the development of high temperature and pressure in the primary and secondary cutting zones. If proper and efficient cooling methods are not employed then the heat developed will adversely affect the efficiency of the cutting process.

Several methods are in practice for cooling and flushing of chips away from the cutting area. Some of these are:

- Flood cooling
- Cryogenic treatment
- Minimum quantity lubrication
- High pressure cooling
- Use of solid coolants
- Use of compressed gas coolant
- Allied cooling [4]

In view of current scenario of green manufacturing, researchers have tried to develop a technology which can help in reducing the environmental pollution. All the metal working fluids (MWF) are known to be environmentally hazardous and harmful to the workers. Thus use of these fluids in least possible quantity is desirable. Minimum quantity lubrication is one such technique which makes use of least possible quantity of MWF. In MQL compressed air typically at pressure of 4-6 bar is mixed with oil. This mixture known as aerosol is sprayed out through a small nozzle of diameter 2mm approx. in the form of oil-mist with a typical flow rate of 50-500 ml/h [4]. In this technique, heat dissipation mainly takes place in the evaporative mode rather than through convection as in conventional wet lubrication or flood cooling [5].

Several researchers have tried to tap the advantages of minimum quantity lubrication in various machining processes such as turning, grinding, drilling, milling etc. The effect of minimum quantity lubrication on the cutting forces, friction and temperature was studied in detail by various researchers.

2.2 Minimum quantity lubrication in turning and milling

2.2.1 Effect of minimum quantity lubrication on cutting force

He et al. carried out a comparative study of high speed turning of bearing steel GCr15 under different cooling environments of dry, external and internal MQL. It was observed that high speed spray could penetrate effectively into the cutting zone thereby reducing the cutting forces as compared to other cooling environment at high cutting speeds [6].

Hadad and Sadeghi carried out a comparative study of the performances of dry, MQL and flood lubricating conditions during machining of AISI 4140 steel. It was observed that highest cutting forces were observed for machining under dry environmental conditions followed by machining under flood lubrication and least value of cutting forces were encountered during machining under MQL lubricating conditions [7].

Dhar et al. carried out turning experiments on AISI 1040 steel under dry and MQL lubricating conditions. It was found that both Fz (cutting force) and Fx (feed force) reduced significantly (5-15%) with increasing cutting velocity under the MQL lubricating environment [8].

Li and Liang conducted an extensive study to analyse the performance of MQL machining with respect to the process parameters. It was found that application of MQL during machining reduced the tangential cutting forces upto a significant limit especially when machining is done at low cutting speeds [9].

Kishawy et al. performed high speed face milling tests on aluminium alloy A356 at different cutting speeds upto 5225 m/min under different cutting environments of dry, flood and MQL. The highest cutting forces were observed for machining under dry conditions and lowest cutting forces were observed for machining under flood cooling. The cutting forces under MQL lubricating conditions were lower than that under dry machining but it was slightly higher that forces developed under flood cooling [10].

2.2.2 Effect of minimum quantity lubrication on temperature

Sharma and Sidhu investigated the effects of dry and minimum quantity lubrication technique during the machining of AISI D2 steel with tungsten carbide tool inserts. The lubrication was done using vegetable oil which is environmentally friendly as compared to other mineral and petroleum based metal working fluids. It was observed that a significant amount of temperature reduction occurred during minimum quantity lubrication as compared to dry machining at all the combinations of machining process parameters [11].

Hadad and Sadeghi performed MQL turning operation on AISI 4140 steel and the performance was compared with machining under dry and flood lubricating conditions. When the oil mist was supplied both on the flank and rake surfaces of the cutting tool, the temperature reduced by about

350 ºC than that in dry machining. When only rake surface was lubricated, the temperature reduced by 200ºC than dry machining. The temperature recorded under flood cooling was approximately 300 ºC lower than that in dry machining. This significant amount of temperature reduction was due to the reduction in cutting forces which consequently reduced the heat liberation and maximum temperature reached [7].

Khan et al. compared the performance of MQL with dry and wet lubricating conditions during the machining of AISI 9310 steel by using vegetable based cutting fluid. It was found that MQL machining was much superior than machining under dry and wet lubricating conditions. Significant reduction in cutting zone temperature (10%) was observed especially at high cutting speeds at which even wet cooling could not produce satisfactory results. This was mainly because at high cutting speeds, it is difficult for the lubricant to penetrate into the cutting zone but in MQL due to high pressure impingement of the cutting fluid, it penetrates better than in other cases. [12].

Dhar et al. conducted turning experiments on AISI 1040 steel under dry and MQL lubricating conditions. It was found that MQL machining reduced the cutting temperatures in a range of 5-10 % depending upon the machining process parameters [8].

Li and Liang carried out extensive investigations to analyse the performance of MQL machining with respect to the process parameters. Temperature was found to get reduced significantly almost under all cutting speeds when machining is done at MQL environment [9].

Dhar et al. carried out comparative study of the performance of MQL with dry machining during the turning of AISI 1040 steel with uncoated cemented carbide inserts. The experimental results indicated that MQL resulted in a significant reduction in the cutting temperature and tool wear. As a consequence of reduction in tool damage, the dimensional accuracy and surface finish also improved to a significant extent. Due to reduction in tool temperature, the damage of the tool cutting edges due to plastic deformation and formation of built up edge reduced thus improving the dimensional accuracy and product quality [13].

2.2.3 Effect of minimum quantity lubrication on surface roughness

Sharma and Sidhu studied the effect of dry machining and machining with minimum quantity lubrication technique on the surface roughness of AISI D2 steel turning. The cutting fluid used was normal vegetable oil on account of its low toxicity and environmental friendly nature. It was observed that machining under MQL technique produced better surface finish as compared to machining under dry condition. This was because dry machining produces high cutting temperatures which results in adhesive and diffusion wear. This causes formation of built up layer also which ultimately deteriorates the surface finish of the final workpiece [11].

He et al. carried out a comparative study of high speed turning of bearing steel GCr15 under different cooling environments of dry, external and internal MQL. Surface roughness was found to get reduced under external and internal MQL lubricating conditions as compared to machining under dry environment [6].

Hadad and Sadeghi performed MQL turning operation on AISI 4140 steel and the results were compared with machining under dry and flood lubricating conditions. Maximum surface roughness was observed for machining under dry environmental conditions whereas least amount of surface roughness was obtained for machining under MQL conditions. This was because machining under MQL lubricating conditions resulted in lesser cutting forces, thus reducing the heat generation and maximum temperature of the chip tool interface, Due to this temperature reduction, adhesive and diffusion wear of the tool was reduced which helped in contributing to the improved surface finish of the final product[7].

Khan et al. performed turning operation on AISI 9310 low carbon steel by using vegetable cutting oil as the cutting fluid under dry, wet and MQL lubricating conditions. It was observed that surface finish improved as a consequence of reduction in tool wear under MQL lubricating conditions as compared to dry and wet lubricating conditions [12].

Dhar et al. carried out comparative study of the effect of MQL and dry machining conditions during turning operation on AISI 1040 steel. It was found that machining under MQL environment resulted in better surface finish as compared to machining under dry environment. This was possibly due to lesser tool wear and reduction in temperature in MQL condition which led to a reduced tendency of built up edge formation thereby resulting in a better surface finish [8].

2.2.4 Effect of minimum quantity lubrication on tool life

Attanasio et al. carried out to research works to determine whether the technique of minimum quantity lubrication (MQL), if applied during turning operation gives some advantages in terms of tool wear reduction. During machining of normalized 100Cr6 steel, it was visible that lubricating the rake surface of a tip by the MQL technique did not produce evident wear reduction as compared to when flank surface was lubricated by MQL. Lubrication on the rake surface gave similar tool life as that under dry cutting conditions whereas it was observed that flank surface lubrication by the MQL technique reduced the tool wear significantly and increased the tool life. The only disadvantage in this technique is the difficulty of lubricant in reaching the cutting surface during machining [14].

Khan et al. performed turning operations on AISI 9310 steel under dry, wet and MQL lubricating conditions using vegetable oil as the cutting fluid. Significant reduction in the tool flank wear was observed for machining under MQL cutting conditions. Abrasion, adhesion and diffusion wear were reduced and tendency of formation of built up edge was also decreased which consequently resulted in an improvement in tool life [12].

Dhar et al. carried out turning experiments on AISI 1040 steel under dry and MQL lubricating conditions. Machining under MQL condition resulted in lesser auxiliary flank wear and hence an improved tool life [8].

Li and Liang carried out extensive investigations to analyse the performance of MQL machining with respect to the process parameters. Due to considerable reduction in the cutting temperature under MQL environment, tool wear was reduced significantly which further helped in improving the tool life [9].

Wang et al. applied MQL lubricating technique to face milling of Inconel 182 which a nickel based super alloy widely used in aerospace industry using uncoated and PVD coated tool inserts. It was found that uncoated tools were not suitable for milling Inconel 182 in all the lubricating environments. On the other hand, MQL nozzle positioned at tool cut into workpiece and positioned at tool cut out of work-piece in down milling as well as MQL nozzle positioned at tool cut out of work-piece in up milling can effectively prolong tool life of PVD coated tool inserts, which can be selected as the optimal lubrication solution for face milling Inconel 182 [15].

Kishawy et al. performed high speed face milling tests on aluminium alloy A356 at different cutting speeds upto 5225 m/min under different cutting environments of dry, flood and MQL. It was found that flank wear for the uncoated carbide inserts was least for the machining under MQL environment especially in the case of machining under high cutting speed. [10].

Aoyama proposed that in high speed drilling, due to large centrifugal forces, the oil mist system is sprayed away from the cutting zone. Thus, the effectiveness of the MQL system is reduced.

Therefore, to make the MQL system more effective and useful even in high speed machining applications, a new design for the same purpose of minimum quantity lubrication was designed. The performance of the new system was first predicted by computer simulation which was later on validated by performing actual cutting tests. The results showed that the technique which involved supply through a spindle proved to be quite effective in cooling the cutting zone even at high cutting velocities and thus increasing the tool life [16].

Li and Liang conducted an extensive study to analyse the performance of MQL machining with respect to the process parameters. The experimental observations taken under consideration were force, temperature, aerosol concentration, and tool flank wear rate. It was found that the application of MQL resulted in a remarkable reduction in the tangential cutting force, especially at low cutting speeds. The MQL shows a strong influence on the cutting temperature over a wide range of speeds, and it also resulted in a lower cutting tool wear rate as compared to completely dry machining [9].

2.2.5 Effect of minimum quantity lubrication on chip morphology

Vasu and Reddy carried out machining operation on Inconel 600 alloy by using minimum quantity lubrication with Al_2O_3 nanoparticles and compared the responses with machining under dry and MQL lubricating conditions. The study of chip morphology showed that light coloured chips were formed when machining was done with nanofluid whereas brown colored chips were formed with dry machining. Further, it was observed that using nanofluid helped in producing discontinuous chips [17].

Khandekar et al. carried out machining on AISI 4340 using Al_2O_3 nanoparticles and compared the output responses with that of machining under dry and MQL cutting conditions. The chip morphology showed that continuous helical chips were formed with dry and MQL cutting conditions while nanofluid resulted in the formation of segmented chips. application of cutting fluid also helped in increasing the helix angle of the chips [18].

Khan et al. compared the performances of machining under dry, wet and minimum quantity lubrication on AISI 9310 alloy steel using vegetable oil-based cutting fluid. The study of chip morphology showed that chips formed under dry and flood lubricating conditions were of continuous ribbon type. Applying minimum quantity lubrication helped in chip reduction coefficient and under surface of chips appeared lighter and brighter [12].

Dhar et al. compared the performances of machining under dry, wet and minimum quantity lubrication on AISI 1040 steel using vegetable oil-based cutting fluid. The study of chip morphology indicated that more discontinuous and light colored chips were produced with cutting under MQL conditions [13].

2.3 Application of minimum quantity lubrication in grinding

Tawakoli et al. made a comparison of performance characteristics for grinding process on 100Cr6 hardened steel under dry, wet and MQL lubrication conditions. It was found that tangential forces were reduced considerably under MQL environment possibly due to better penetration of the lubricant in the grinding zone under high air pressure. Due to better lubrication friction coefficient and specific energy consumption was also reduced between the rubbing surfaces which resulted in a better surface finish [19].

Tawakoli et al. investigated the effect of various process parameters such as oil flow rate, air pressure, MQL nozzle position and distance from the wheel–work-piece contact zone was investigated thoroughly in the process of grinding. It was observed that the position of nozzle during the process has significant effect on the overall performance. An angular position of the nozzle at 10º- 20º to the surface of the work-piece resulted in the most optimal performance.

Also, the distance of the nozzle from the grinding zone was also critical in deciding the process performance. The oil mist needed to be applied to the work-piece surface in order to achieve maximum efficiency in the performance [20].

Silva et al. studied the behavior of minimum quantity lubrication in grinding hardened AISI 4340 steel and compared the results obtained with conventional lubricating system. The performance evaluation was done on the basis of surface integrity of the ground surface and the grinding wheel wear. It was found that the best performance could be obtained under MQL environment with air flow rate 26.4 m/s and lubricant flow rate as 40 ml/h. It had a positive effect on the overall surface integrity which included surface roughness, micro hardness and micro structure analysis [21].

Silva et al. carried out grinding experiments on ABNT 4340 steel using aluminium oxide nad super abrasive cubic boron nitride (CBN) grinding wheels. The analysis indicated that surface roughness and grinding wheel wear reduced significantly when the experiment was carried out under MQL lubricating condition. The performance of aluminium oxide wheel was better than that of CBN wheel under MQL condition. However, surface roughness was less when aluminium oxide wheel was used. The tangential cutting forces were also reduced under MQL environment [22].

Various kinds of vegetable or mineral oils can be used as lubricant in the minimum quantity lubrication applications. However, considering the costs involved in the production chain, the choice of fluid depends upon their characteristics such as biodegradability, oxidation stability, storage stability etc. Extensive analysis was done by **Suda et al.** on various cutting oils. Their analysis showed that synthetic polyol esters are the best choice for MQL cutting considering their performances in the above mentioned criteria [23].

Hadad et al. carried out investigation for temperature and energy partition in the MQL grinding using Al_2O_3 and CBN super abrasive grinding wheels and hardened 100Cr6 (AISI 52100) steel as the work piece material. The output responses considered for investigation were grinding forces, grinding temperature and surface finish. It was observed that grindability of 100Cr6 hardened steel increased significantly by employing the MQL technique in the grinding process. Grinding forces were reduced considerably and the surface finish was found to improve in comparison to other grinding conditions [24].

2.4 Applications of powder mixed cutting fluids under MQL environment

It was observed that MQL could be used as an alternative to the dry and flood lubricating conditions only at mild cutting conditions. Under aggressive machining conditions such as high cutting speed, as soon as the small quantity of oil mist comes in contact with the machining zone, it vaporizes without effectively removing the heat. Thus, there arose a need to enhance the properties of the MQL fluid in such a way that it can prove to be beneficial in all the cutting conditions. One such solution provided was addition of small sized thermally conducting particles, having lubricating properties to the base fluid medium which can cool as well as lubricate the cutting zone.

Gopal and Rao used graphite as a solid lubricant in grinding of Silicon carbide. Tangential cutting force, temperature, specific energy and surface roughness were found to be reduced as compared to when grinding was done under dry environment. This resulted in a greater material removal rate and a lesser wheel wear. Thus, grinding under graphite environment resulted in a greater productivity and a better product quality [25].

Singh and Rao performed hard turning of AISI 52100 steel using solid lubricants – graphite and molybdenum disulfide of 2μm particle size. The effect of graphite and molybdenum disulfide lubrication during the process was studied and the results were compared with that of machining under dry environment. It was found that surface roughness and cutting forces were reduced in case of machining under graphite and molybdenum disulfide environment nad that the best performance in terms of reduction of cutting forces and surface roughness was that of molybdenum disulfide. These results established the superiority of molybdenum disulfide as a lubricant material over that of graphite [26].

Shen et al. applied water based Al_2O_3 and diamond nanofluids in the grinding of cast iron under MQL conditions and compared the results with dry and wet lubricating conditions. Nanofluid lubrication helped in reducing the grinding forces, improving surface roughness and preventing the burning of workpiece by providing an efficient cooling system [27].

Verma et al showed that Molybdenum disulfide nanoparticles had excellent tribological characteristics [28]. Inspired by this, **Shen et al.** applied MoS_2 nanoparticles in various base fluids in the grinding of cast iron. The tangential grinding forces, normal forces and frictional force were significantly reduced. G-ratio was also improved signifying a substantial improvement in grinding performance [29].

To investigate the effect of carbon nano tubes as nano lubricant in grinding, **Shen and Shih** mixed multi walled carbon nano tubes in soybean oil and performed grinding using vitrified bond CBN grinding wheel on Dura-Bar 100-70-02 ductile iron as work material. It was observed that addition of CNT in soybean oil could not significantly reduce the grinding forces. Maximum temperature reduction and improvement in surface finish was obtained with flood cooling [30].

Krishna et al. evaluated the performance of nano boric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel. As expected, addition of nano boric acid particles increased the thermal conductivity, heat transfer coefficient and reduced the specific heat. It was further observed that 0.5% concentration of nano boric acid performed the best in reducing cutting temperature, tool flank wear and surface roughness [31].

Kwon et al. studied the tribological behavior of the nanographene additives in different cutting environments such as dry, water soluble oil and vegetable oil. Various tribological tests such as wetting angle measurement, friction tests using a ball-on-disk setup, and MQL ball milling test were conducted under a variable sets of loads and speeds. It was observed that the addition of exfoliated nanographene particles in the cutting fluid successfully improved the wettability and surface finish of the cutting surface. The best cutting performance was exhibited by MQL using 0.1wt % xGnP with 1 µm diameter. However the hBN platelets were found to be more advantageous than nano graphene particles in reducing flank and central wear inspite of having similar friction behaviours [32].

Vasu and Reddy investigated the machinability characteristics of Inconel 600 alloy under different cutting environments such as dry, MQL and Al_2O_3 nanoparticles suspended in vegetable oil was investigated. The characterization was done on the basis of surface roughness, tool wear, cutting forces, and temperature dissipation. The experiment results demonstrated that the significant parameters which influenced the tool wear were the feed rate and the depth of cut. Further nanofluids MQL using Al_2O_3 in 6% volume concentration showed the best performance as compared to other cutting environments [33].

Nam et al. MQL application using nanodiamond particles in the micro drilling process was carried out by. Paraffin and vegetable oil were taken as the base cutting fluids. It was observed that nano diamond particles could effectively reduce the drilling torques and thrust forces. Further paraffin based nano fluid proved to be more effective than vegetable oil based nanofluid in terms of reducing the torque and thrust force [34].

Khandekar et al. compared the wettability characteristics and cutting performance of 1% Al_2O_3 nanofluid, water and conventional cutting fluid on AISI 4340 using uncoated cemented carbide insert. Addition of 1% Al_2O_3 nanoparticles greatly enhanced the Wettability characteristics of the base fluid. A high reduction in tool wear, cutting force and surface roughness values was also observed in case of nano cutting fluids as compared to dry and conventional cutting fluid [35].

Inspired by the positive results of nanofluids in turning and drilling, many researchers started exploring the applicability of nanofluids in the grinding process as well. **Mao et al.** applied water based Al_2O_3 nanofluid in grinding of AISI 52100 steel. It was stated that due to the ball bearing effect of the nano particles, Al_2O_3 based nanofluids have better lubricating properties. Grinding forces and grinding temperatures were significantly reduced and similarly ground surface morphology and surface roughness was considerably improved in the nano fluid cutting environment [36].

Setti et al. carried out Taguchi and Response surface analysis in the grinding of Ti-6Al-4V using Al_2O_3 nano fluid. As expected nanofluid MQL reduced the grinding force and improved the surface finish. It was also observed that increasing the volumetric percentage of nano particles did not result in increasing the efficiency proportionally [37].

Kalita et al. used MoS_2 nano particles in paraffin and soybean oils in the grinding process using cast iron and EN24 steel as the work piece materials. It was concluded that MQL grinding using nanofluids reduced the specific energy consumption and frictional losses and increased the G ratio [38].

Lee et al. extended the applications of Al_2O_3 nanofluids and nanodiamond fluids to micro grinding process. Nano diamond particles were found to be more effective than Al_2O_3 nano particles in reducing grinding forces and enhancing the surface quality. On the other hand, nano Al_2O_3 particles proved to be more effective in reducing the surface roughness [39].

Mao et al. studied the effect of nozzle spraying direction during surface grinding of hardened AISI 52100 steel. An angular position of the nozzle towards the grinding wheel provided the most optimal grinding performance. Increase in air pressure resulted in reduction in grinding forces, surface roughness and grinding temperature. Better grinding performance was obtained with shorter spraying direction [40].

Roy and Ghosh carried out high speed turning of AISI 1040 steel using multi walled carbon nano tube (MWCNT) based nanofluid and multi layered cemented carbide inserts. The experiments were carried out in dry, wet and MQL environment. It was found that nanofluid resulted in the maximum reduction in the tool tip temperature that amounted to nearly 10-30%. The reduction was found to be even more than machining under flood lubricating condition. The nano fluid thus exhibited its greater heat absorbing capacity as compared to conventional fluid [41].

Khalilpourazary and Meshkat investigated the effect of alumina based nanofluid during the hobbing process. The nanoparticles were mixed in mineral-based oil 25W-50 and the hobbing process was done on DIN1.7131 using both nano fluid as well as fluid without nnaoparticles. The comparative study showed that crater and flank wear of the hob tool reduced considerably under nanofluid environment. It was also found that the average surface roughness of the manufactured gears was reduced under nano lubrication. [42]

Sayuti et al. conducted end milling of AISI 6061-T6 aluminium alloy using SiO_2 dispersed in ECOCUT SSN 322 cutting fluid. The concentration of nanoparticles was varied in the range of 0 to 1 %. It was found that increasing the nanoparticle concentration led to the formation of thin film of SiO_2 on the machined surface. This film provided a ball bearing effect which reduced cutting forces, cutting temperature and improved the surface finish of the final product [43].

Rahmati et al. studied the surface morphology of AL6061-T6 aluminium alloy during its end milling. Molybdenum disulfide based nanofluid was used as the cutting fluid. It was observed that MoS_2 provided rolling and ball bearing effect which helped in reducing the surface roughness to a significant extent. Least value of surface roughness could be obtained when the nanoparticle concentration was kept at 0.5%. [44]

Rahmati et al. applied MoS_2 based nanolubrication in the end milling of AL6061-T6 aluminium alloy. The effect of MQL parameters such as air pressure, nozzle position and nano particle concentration on the output responses such as cutting forces, cutting temperature and surface roughness was investigated. It was found that lowest cutting forces were obtained at 1% nanoparticle concentration and lowest cutting temperature and surface roughness was obtained at 0.5% nanoparticle concentration. 30º nozzle orientation was best suited to produce lowest cutting forces and minimum cutting temperature whereas 60º nozzle orientation resulted in lowest surface roughness. The air pressure should be kept at 4 bar to get the best output responses. [45]

Mao et al. investigated the suspension stability of Al_2O_3 nano fluid which is applied in minimum quantity lubricant grinding. It was found that the nanofluid had poor suspension stability under short time ultra sonic vibrations. The suspension stability could be improved by using 0.5% nanoparticles and increasing the ultrasonic vibrations to about 1 hour. Due to better dispersing characteristics under these conditions the resulting nanofluid has got better heat dissipating and lubricating properties [46].

Amrita et al. investigated the effect of nano graphite dispersed soluble oil as the cutting fluid during the machining of AISI 1040 steel using cemented carbide tool inserts. The performance measures taken were cutting forces, cutting temperatures, tool flank wear, surface roughness and chip morphology. It was found that nanoparticle based cutting fluid showed better performance as compared to dry machining, flood lubrication as well as MQL lubrication using conventional oil without nano particles. [47]

Saravanakumar et al. carried out experiments involving silver nanoparticles based cutting fluid during turning operation. The cooling and lubricating characteristics of the nanofluid was investigated and compared with that of cutting fluid without nano particle. It was found that cutting forces, surface roughness and cutting temperatures reduced significantly when machining under nanofluid [48].

Sayuti et al. investigated the effect of silicon dioxide (SiO_2) based nanofluid on the surface roughness and tool wear during hard turning of AISI 4140 steel. It was observed that least amount of tool wear was obtained when nanoparticle concentration was 0.5%, nozzle angle was 60º and air pressure was 2 bar. Best surface finish was obtained with 0.5% nanoparticle concentration, 30º nozzle angle and comparatively lesser air pressure [49].

Mao et al. investigated the role of the nanofluid in grinding operation by conducting friction and wear experiments which can establish various tribological properties of the nanofluid. They observed that nanoparticle based fluid showed a superior anti wear characteristics which led to a reduction in tangential cutting forces and improved the surface texture. [50].

CHAPTER 3

OBJECTIVE

From the survey of past literature, it has been observed that much work has been reported on the applications of phenomenon of minimum quantity lubrication in various material removal processes such as turning, milling, grinding, drilling etc. The effect of minimum quantity lubrication on various performance measures like cutting force, surface roughness, cutting zone temperature, chip characteristics and tool life has been investigated. Recent research work showed addition of nano particles in the cutting fluid has a strong potential in improving the performance of machining and grinding processes by virtue of enhanced cooling and lubrication properties of the nano particles. Although MoS_2 is widely regarded as solid lubricant material, the effect of addition of MoS_2 particles (having average grain size in the range of nano or micro meter) has hardly been reported in turning operation. Moreover, there is a lack of systematic investigation on the influence of base fluid on the performance of powder-mixed MQL during machining or grinding.

In order understand the influence of addition of solid lubricant powder on MQL, molybdenum disulfide has been selected for the current study. To study the effect of base fluid on powder-mixed MQL, two different base fluids have been used conventional water soluble cutting fluid and light paraffin oil. It is also essential to recommend optimal cutting condition for machining under powder-mixed MQL condition. Since, machining of austenitic stainless steel is considered difficult primarily due to low thermal conductivity and tendency of strain hardening, AISI 316L grade stainless steel has been considered as workpiece material for turning operation during the current research work. Therefore, the study has been planned and undertaken with the following broad objectives:

1. To study the effect of MoS_2 powder-mixed cutting fluids under MQL mode on various machinability characteristics such as cutting force, cutting temperature, surface roughness, chip thickness and macro morphology of chips and compare the results with that of cutting fluid without the use of MoS_2 powder during turning of AISI 316L austenitic stainless steel.
2. To investigate the influence of concentration of MoS_2 powder along with cutting speed and feed with the help of response surface methodology (RSM)-based design of experiments (DOE) on cutting force, cutting temperature, surface roughness and chip thickness during turning of AISI 316L stainless steel.
3. To undertake a comparative study of the effect of paraffin oil and conventional water soluble cutting oil as base fluids on the performance of powder-mixed MQL during machining austenitic stainless steel.
4. To optimize the various output responses during turning under powder-mixed MQL using grey relational analysis and thus to determine the most optimal parametric combination which can yield the best possible performance characteristics.

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 Experimental Setup

The experiment involved turning process to be carried out on a cylindrical job of stainless steel (AISI 316L). The workpiece considered had the initial diameter of 75mm and length of 350mm. All the turning experiments were carried out on a heavy duty lathe machine (Make: Hindustan Machine Tools (HMT) Ltd., Bangalore, India; Model: NH26), shown in Fig. 2.

Fig. 4.1: Experimental setup for carrying out the turning experiments

4.2 Selection of workpiece and tool material

The machining operations were carried out on austenitic stainless steel AISI 316L having the chemical composition as shown in Table 4.1 and physical characteristics as shown in Table 4.2.

Table 4.1: Chemical composition of Austenitic stainless steel AISI 316L

Elements	C	Mn	Si	P	S	Cr	Mo	Ni	N
Wt %	0.03	2.0	0.75	0.045	0.03	18.0	3.0	14.0	0.10

Table 4.2: Physical properties of Austenitic stainless steel AISI 316L

Physical Properties	**Magnitude**
Density	8000
Poisson's Ratio	0.27–0.30
Elastic Modulus (GPa)	193
Tensile Strength (Mpa)	515
Yield Strength (Mpa)	205
Vickers Hardness	260
Thermal Conductivity (W/(mK))	16.3

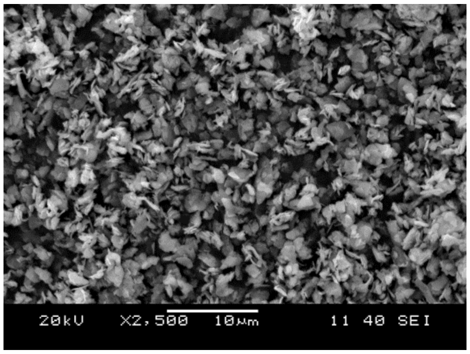
The machining was carried out using uncoated cemented carbide tool inserts of P30 grade having the insert designation as SCMT 120408. The tool holder used was of ISO SSBR 2020K12 designation (make: Kennametal, India).

4.3 Selection of powder and cutting fluids

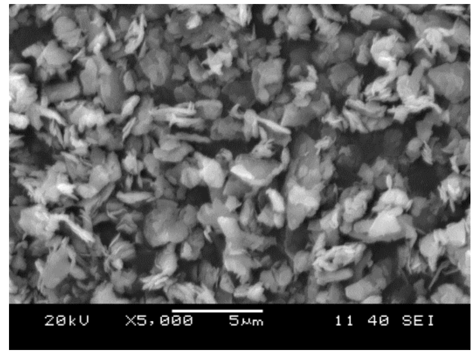
Molybdenum disulfide (MoS_2) has got excellent tribological properties and when it is added to paraffin oil, it performs extremely well as a lubricant under high pressure conditions []. Owing to its exceptional lubricating characteristics, Molybdenum disulfide (supplier: Sigma Aldrich) was chosen for preparing the powder mixed cutting fluid to be applied onto the cutting zone. The properties of molybdenum disulfide are shown in Table 4.3. The scanning electron microscopic (SEM) images depicting the microstructure of MoS_2 nanoparticles are shown in Fig. 4.2 (a) and Fig. 4.2 (b). Two cutting fluids were chosen as the base fluids into which the nanoparticles had to be added to prepare the nanofluids.

- Conventional cutting oil

- Light paraffin oil



(a)



(b)

Fig. 4.2 SEM images showing the microstructure of MoS_2 at magnification of (a) x2500 and (b) x5000

Table 4.3: Properties of molybdenum disulfide

Molecular formula	MoS_2
Molar mass	160.07 g/mol
Appearance	black/lead-gray solid
Density	5.06 g/cm^3
Melting point	1185 °C
Solubility in water	Insoluble
Crystal structure	Hexagonal
Particle size	1µm (Appx)

Two cutting fluids were chosen so that comparative study can be done on the performance of both the cutting fluids in terms of their thermal and tribological behavior. The physical properties of light liquid paraffin oil are shown in Table 4.4.

Table 4.4: Properties of light liquid paraffin oil

Appearance	Clear colorless liquid
Specific gravity	0.8 g/ml
Vapor density (air =1)	>1
Vapor pressure	< 0.01 mm Hg
Solubility	Water immiscible, soluble in petroleum products
Flash point	>180ºC
Specific heat capacity	2.13J/kg/ºC

4.4 Preparation of cutting fluids

The experiments were carried out under minimum quantity lubrication (MQL) environment. Two cutting fluids i.e. conventional cutting oil and light paraffin oil was used as the base fluids. Molybdenum disulfide particles were added into the base fluid and mixed thoroughly to avoid any particle settlement at the base due to difference in specific gravity. Four types of MQL environment was set up.

1. Conventional cutting fluid MQL
2. Conventional cutting fluid with varying concentrations of MoS_2 nanoparticles
3. Light paraffin oil
4. Light paraffin oil with varying concentrations of MoS_2 nanoparticles

4.5 Setup for minimum quantity lubrication

The cutting fluid needed to be supplied using minimum quantity lubrication technique. Therefore, an MQL setup was developed for creating the required oil-mist to be supplied onto the cutting zone. The setup used for MQL application is shown in Fig. 4.3 and the conditions under which MQL is carried out is shown in Table 4.5.

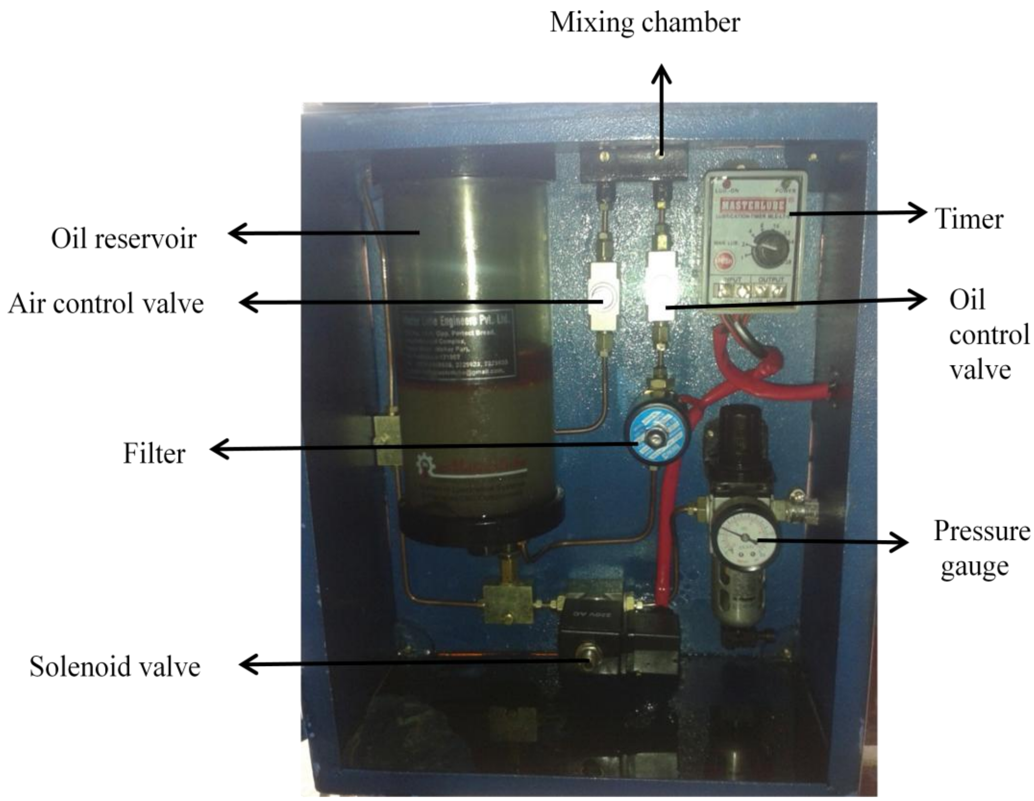


Fig. 4.3: Setup for supplying cutting fluid with minimum quantity lubrication technique

Table 4.5: Conditions under which Minimum quantity lubrication is carried out

MQL Flow Rate	5ml/hr
Air pressure	4 -6 bar
MQL nozzle distance from contact zone(d)	20mm
Horizontal angle to the work-piece (α)	α=15°

4.5.1 Working of MQL setup

The setup used for applying minimum quantity lubrication in machining operations is commercially called as an 'oil mist lubricator'. The working of an oil mist lubricator is shown in Fig. 4.4.

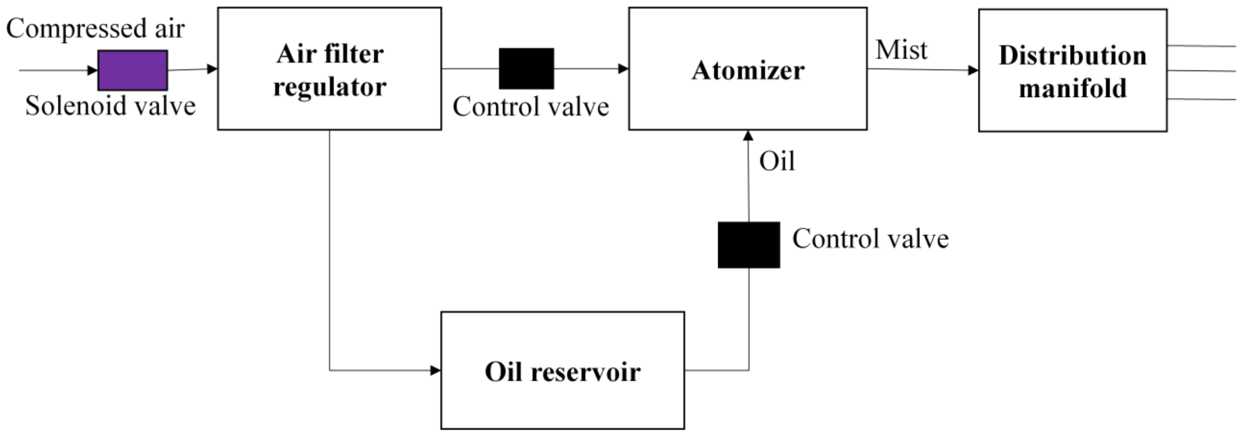


Fig. 4.4: Flowchart depicting the working of oil mist lubricator

The oil mist lubricator functions in the following manner.

1. Highly compressed air with typical air pressure of 4-6 bar is supplied into the air filter via a solenoid valve.
2. The air filter removes any impurity or contaminations that may have come along with the supplied air so as to keep the equipment clean and dirt free.
3. In the mean time cutting fluid from the oil reservoir is supplied to the mixing chamber via an oil control valve. Oil control valve helps to control the flow rate of oil to be supplied.
4. In the mixing chamber, the compressed air from the filter via air control valve and the cutting fluid get mixed to form an aerosol known as oil-mist.
5. This oil mist is then supplied to the cutting zone through a very small holed (< 2 mm) nozzle.

4.6 Design of experiment

The experiments were carried out based on Response surface methodology (RSM). The design of experiments is shown in Table 4.6 as shown below.

Table 4.6: Design of experiment based on Response surface methodology

Run No.	Cutting Velocity (m/min)	Feed (mm/rev)	Concentration (weight %)
1	130	0.15	6
2	60	0.10	9
3	100	0.20	6
4	100	0.10	6
5	130	0.10	9
6	130	0.20	3
7	60	0.15	9
8	100	0.15	6
9	100	0.20	6
10	130	0.15	3
11	100	0.10	6
12	100	0.20	6
13	60	0.15	3
14	100	0.15	3
15	100	0.15	6
16	60	0.15	6
17	100	0.15	9
18	100	0.20	6
19	130	0.10	9
20	60	0.10	3

The machining was carried out by keeping the depth of cut equal to 1mm and length of cut = 30mm for all the runs in order to study the effect of variation of cutting velocity and feed. The cutting velocity was varied over 3 levels: 60 m/min, 100 m/min and 130 m/min. The feed was varied as 0.1 mm/rev, 0.15 mm/rev and 0.2 mm/rev and concentration of nanoparticles in the cutting fluid was varied as 3%, 6% and 9% by weight of the cutting fluid.

All the experimental conditions under which the turning of stainless steel AISI 316L was carried out have been summarized in Table 4.7.

Table 4.7: Experimental Conditions for Turning

Workpiece material	AISI 316L stainless steel
Insert used	Uncoated cemented carbide insert (P 30 grade)
Insert designation	SCMT 12 04 08
Tool geometry	−6°, −6°, 6°, 6°, 15°, 75°, 0.8 (mm)
Cutting velocity (m/min)	60, 100, 130
Feed (mm/rev)	0.1, 0.15, 0.2
Concentration of MoS_2 (wt%)	3,6,9
Depth of cut (mm)	1
Length of cut (mm)	30
Environment	MQL

During machining, the output responses that were measured were cutting forces and cutting temperature. Cutting forces were measured with the help of a piezoelectric dynamometer (make: Kistler Instrument Corporation). The temperature measurement was done with the help of a K-type thermocouple. The hot junction of the thermocouple was attached at the base of the tool holder with the help of an epoxy resin just below the tool insert. The cold junction of the thermocouple was attached to a temperature measuring device. The thermocouple arrangement for temperature measurement is shown in Fig. 4.5.

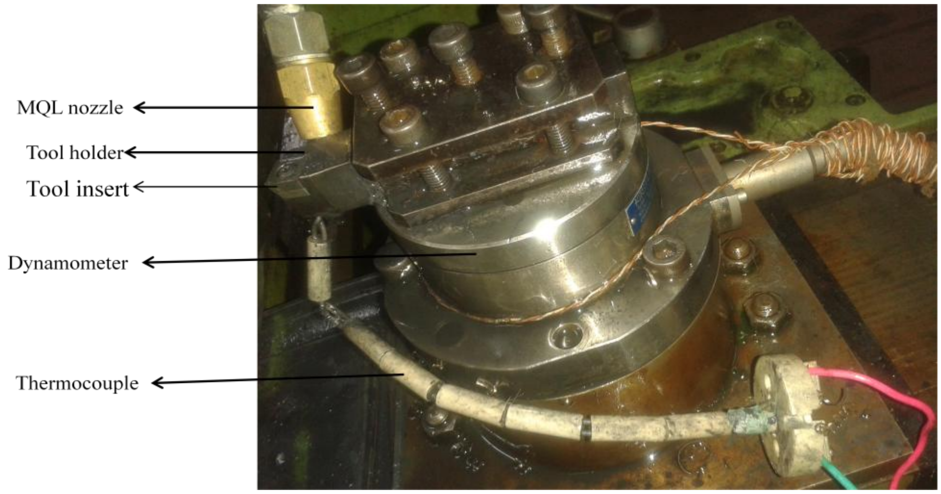


Fig. 4.5 Thermocouple arrangement for temperature measurement

After the machining runs were carried out over one full length of the workpiece, the surface roughness for each run was measured using a talysurf (make: Taylor Hobson: Surtronic 3+) as shown in Fig. 4.6. The talysurf was mounted on the workpiece by using horizontal supports on both the sides and then the surface roughness for each length of cut was measured. The chips were collected and chip thickness was measured using a digital vernier caliper (make: Mitutoyo Corporation) and chip reduction coefficient was calculated.

Fig. 4.6: Talysurf for surface roughness measurement (make: Taylor Hobson: Surtronic 3+)

4.7 Grey relation analysis (GRA)

In Grey relational analysis, black systems refer to those systems for which no information is available, white systems refer to those systems for which all the information correlating the data and the responses are present and grey systems refer to those systems for which some information is known in advance. Grey system level lies in between that of black and white system levels. Grey relational analysis finds its usefulness in multi response problems in which single objective optimization techniques cannot be applied.

Following procedure was adopted for optimizing multi response systems using GRA technique.

1. *Data preprocessing (Normalizing the output responses)*

In this step, all the output responses such as cutting force, cutting temperature, surface roughness and chip thickness were normalized in the range of 0 and 1. Those output responses which need to be maximized are normalized using ‘higher the better characteristic’ and the output responses which need to be minimized are normalized by applying ‘lower the better characteristic’. In our case, all the output responses namely, cutting force, cutting temperature, surface roughness and chip thickness are of 'lower the better' characteristic and hence will be minimized. Thus, the following equation will be used to normalize the above stated output responses:

$$X_i^*(k) = \frac{\max \mathrm{yi(k)} - \mathrm{yi(k)}}{\max \mathrm{yi(k)} - \min \mathrm{yi(k)}} \tag{1}$$

Where, i= 1,2…m; k= 1,2..n; m is the total number of experimental runs and n is the number of output responses; min $y_i(k)$ and max $y_i(k)$ are the minimum and maximum values of the output response under consideration. $X_i^*(k)$ is the obtained normalized value.

2. *Grey relational coefficient calculation*

After normalizing the data, grey relational coefficient is evaluated which represents the correlation between the optimal and normalized sequences. The grey relational coefficient can be calculated as shown below:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{\max}}{\Delta_{0i}(p) + \zeta\Delta_{\max}} \tag{2}$$

Where, $\xi_i(k)$ represents the grey relational coefficient, ζ is the identification coefficient (or distinguishing factor) which is generally taken to be equal to 0.5. Δ_{min} and Δ_{max} are the minimum and maximum values of the normalized sequence.

3. *Grey relational grade calculation*

Grey relational grade represents the degree of influence that the normalized sequence exerts over the original sequence. A higher value of grey relational grade represents a relatively higher degree of influence exerted on the original sequence by the comparative sequence and vice versa. Grey relational grade is mathematically evaluated as the weighted sum of the grey relational coefficients as shown below:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i\,(k) \tag{3}$$

γ_i represents the grey relational grade for the corresponding sequence. In GRA, the weighted sum of the grey relational coefficients is approximated to the average value of the coefficients. Since, higher grey relational grade represents the most influential sequence order, therefore that combination of process parameters is expected to yield best result. Hence, the combination corresponding to the highest grey relational grade is considered to be the optimal combination of process parameters.

4.8 Confirmation test

The results obtained from grey relational analysis needed to verified by performing actual experiment corresponding to the optimal combination of the process parameters. The expected or predicted grey relational grade for that optimal run is evaluated as shown below:

$$\eta_{predicted} = \eta_a + \sum_{i=1}^{q} (\eta_i - \eta_a) \qquad (4)$$

The actual experimental run is then performed and the grey relational grade is then compared with the predicted grey relational grade.

CHAPTER 5

RESULTS AND DISCUSSION

After machining, the output responses were measured and tabulated as shown in Table 5.1, 5.2, 5.3 and 5.4.

Table 5.1: Output responses for machining with conventional oil and MoS_2 particles

Run no	Vc (m/min)	f (mm/rev)	Concentration of MoS_2 (wt%)	Fz (N)	T (ºC)	Ra (μm)	Chip thickness (mm)
1	130	0.2	9	106	34	0.4	0.2667
2	100	0.15	6	99	39	1.4	0.1933
3	100	0.15	6	109	36	1.4	0.2667
4	100	0.15	6	105	40	1.2	0.3433
5	100	0.15	6	109	36	0.8	0.1800
6	130	0.2	3	100	35	1.0	0.2700
7	100	0.15	6	96	40	1.8	0.3733
8	100	0.2	6	98	38	1.4	0.2773
9	60	0.2	3	96	35	1.3	0.3667
10	100	0.1	6	104	36	1.8	0.2033
11	100	0.15	9	93	34	0.5	0.1967
12	130	0.1	3	99	42	0.6	0.2786
13	60	0.2	9	97	38	0.4	0.2981
14	100	0.15	6	103	40	1.6	0.3933
15	100	0.15	3	105	44	1.4	0.2453
16	130	0.1	9	147	31	0.2	0.2775
17	60	0.1	3	101	43	1.4	0.1833
18	60	0.1	9	94	36	0.4	0.2430
19	60	0.15	6	100	38	1.0	0.3633
20	130	0.15	6	102	41	1.8	0.1767

Table 5.2: Output response table for machining with conventional oil as the cutting fluid

Run no.	Vc (m/min)	f (mm/rev)	Fz (N)	Ra (μm)	T (ºC)	Average chip thickness (mm)
1	130	0.15	110	1.9	47	0.2567
2	60	0.10	104	0.8	39	0.1833
3	100	0.15	115	0.6	41	0.2733
4	100	0.20	118	1.8	43	0.3567
5	130	0.10	127	1.0	44	0.1700

6	130	0.10	113	1.2	43	0.1800
7	60	0.20	122	2.0	45	0.3800
8	100	0.15	114	1.6	45	0.2533
9	100	0.15	114	1.2	47	0.2533
10	130	0.20	129	1.8	54	0.3233
11	100	0.15	112	1.2	48	0.2400
12	100	0.10	111	1.9	37	0.1833
13	60	0.20	119	1.5	45	0.1956
14	100	0.15	113	1.2	42	0.2500
15	100	0.15	114	1.4	44.6	0.2545
16	60	0.15	107	1.2	41	0.1933
17	100	0.15	112	1.2	44.5	0.2534
18	100	0.15	113	1.3	44	0.2567
19	130	0.20	118	1.8	43	0.3567
20	60	0.10	108	1.8	43	0.1933

Table 5.3: Output response table for machining with paraffin oil and MoS_2 as the cutting fluid

Run no.	Vc (m/min)	f (mm/rev)	Concentration (wt%)	Fz (N)	T (ºC)	Ra (μm)	Chip thickness (mm)
1	60	0.2	3	127	44	1.6	0.4067
2	100	0.15	6	120	42	1.4	0.2733
3	130	0.1	3	115	51	2.8	0.18
4	100	0.15	6	118	43	1.4	0.2533
5	100	0.1	6	118	43	1.2	0.19
6	100	0.15	6	117	45	1.2	0.26
7	100	0.15	6	112	42	1	0.25
8	130	0.2	9	110	45	3.2	0.4733
9	60	0.1	9	118	45	0.8	0.1833
10	100	0.15	3	124	49	1.2	0.2667
11	130	0.1	9	114	42	1.4	0.1867
12	100	0.15	6	119	42	1.2	0.26
13	130	0.2	3	113	47	1.8	0.3433
14	100	0.15	9	117	41	1.4	0.2667
15	100	0.2	6	120	44	1.8	0.3633
16	130	0.15	6	113	43	1.4	0.2567
17	60	0.1	3	121	50	1.6	0.21
18	100	0.15	6	118	43	1.8	0.2633
19	60	0.2	9	120	42	2	0.383
20	60	0.15	6	120	42	1.2	0.27

Table 5.4: Output response table for machining with paraffin oil as the cutting fluid

Run no.	Vc (m/min)	f (mm/rev)	Fz (N)	Ra (μm)	T (ºC)	Average chip thickness (mm)
1	130	0.15	123	1.0	50	0.2800
2	60	0.10	104	1.6	51	0.2730
3	100	0.15	128	1.6	47	0.2700
4	100	0.20	132	1.4	50	0.3467
5	130	0.10	99	0.6	50	0.1733
6	130	0.10	65	0.8	49	0.2400
7	60	0.20	132	1.8	52	0.3767
8	100	0.15	124	0.8	49	0.1767
9	100	0.15	126	1.0	51	0.2700
10	130	0.20	106	2.0	50	0.3430
11	100	0.15	112	1.2	48	0.2423
12	100	0.10	119	0.6	48	0.20000
13	60	0.20	129	1.8	51	0.3767
14	100	0.15	126	1.0	51	0.2567
15	100	0.15	114	1.4	44	0.2545
16	60	0.15	119	0.8	47	0.2767
17	100	0.15	122	0.8	50	0.2534
18	100	0.15	123	1.3	44	0.2567
19	130	0.20	173	1.8	53	0.3567
20	60	0.10	110	0.6	52	0.2100

5.1 Effect of cutting conditions on various machinability characteristics under different MQL environments through RSM based surface plots

5.1.1 Surface plots for the output responses obtained under the cutting environment of conventional fluid and MoS_2 based cutting fluid

Response surface methodology is a statistical technique which is used to analyse the interrelated effect of different process parameters on the output response. Surface plots are generated to graphically represent the combined effect of different process parameters. The current experimental work involves the correlated influence of cutting velocity, feed and concentration on different output responses. Surface plots for different output responses under the cutting environment of MoS_2 mixed conventional cutting fluid are shown in Fig. 5.1-5.3.

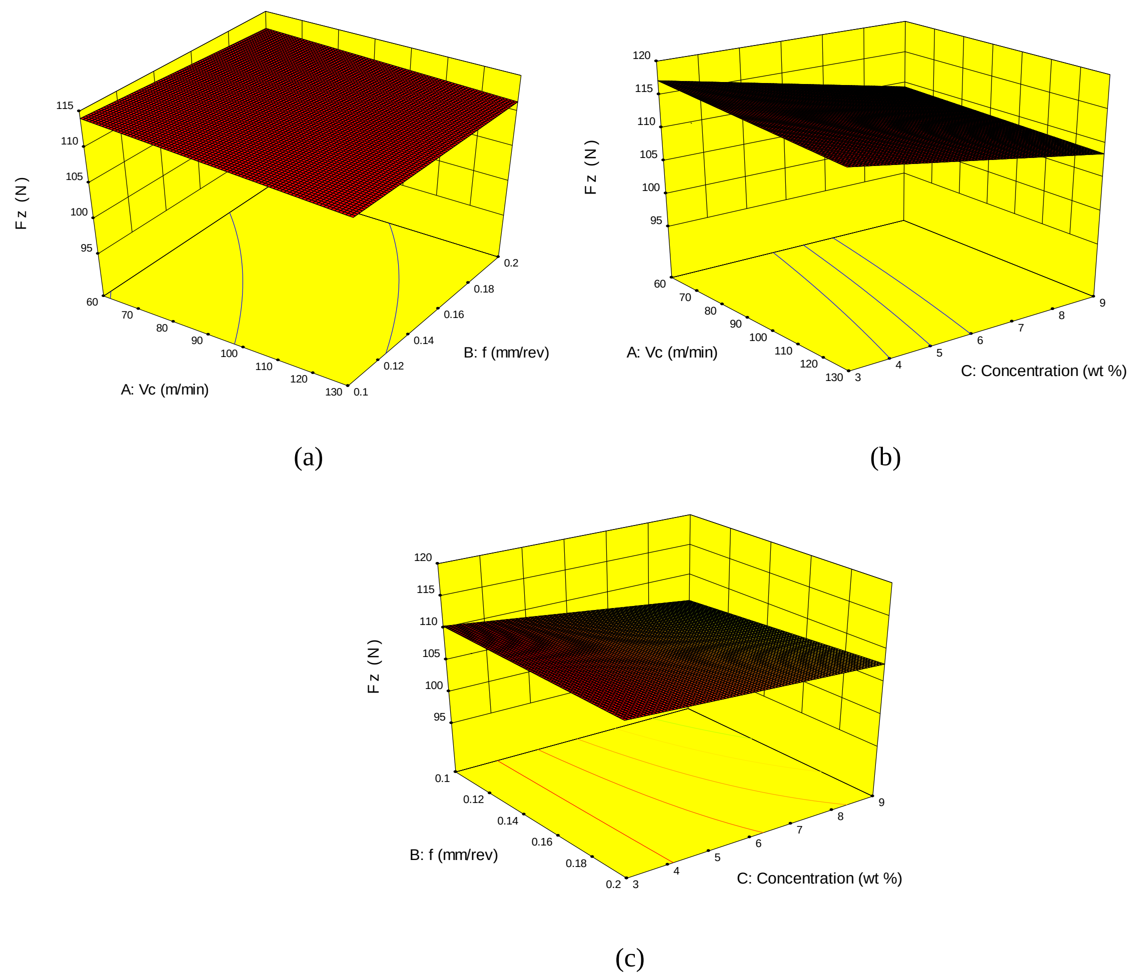


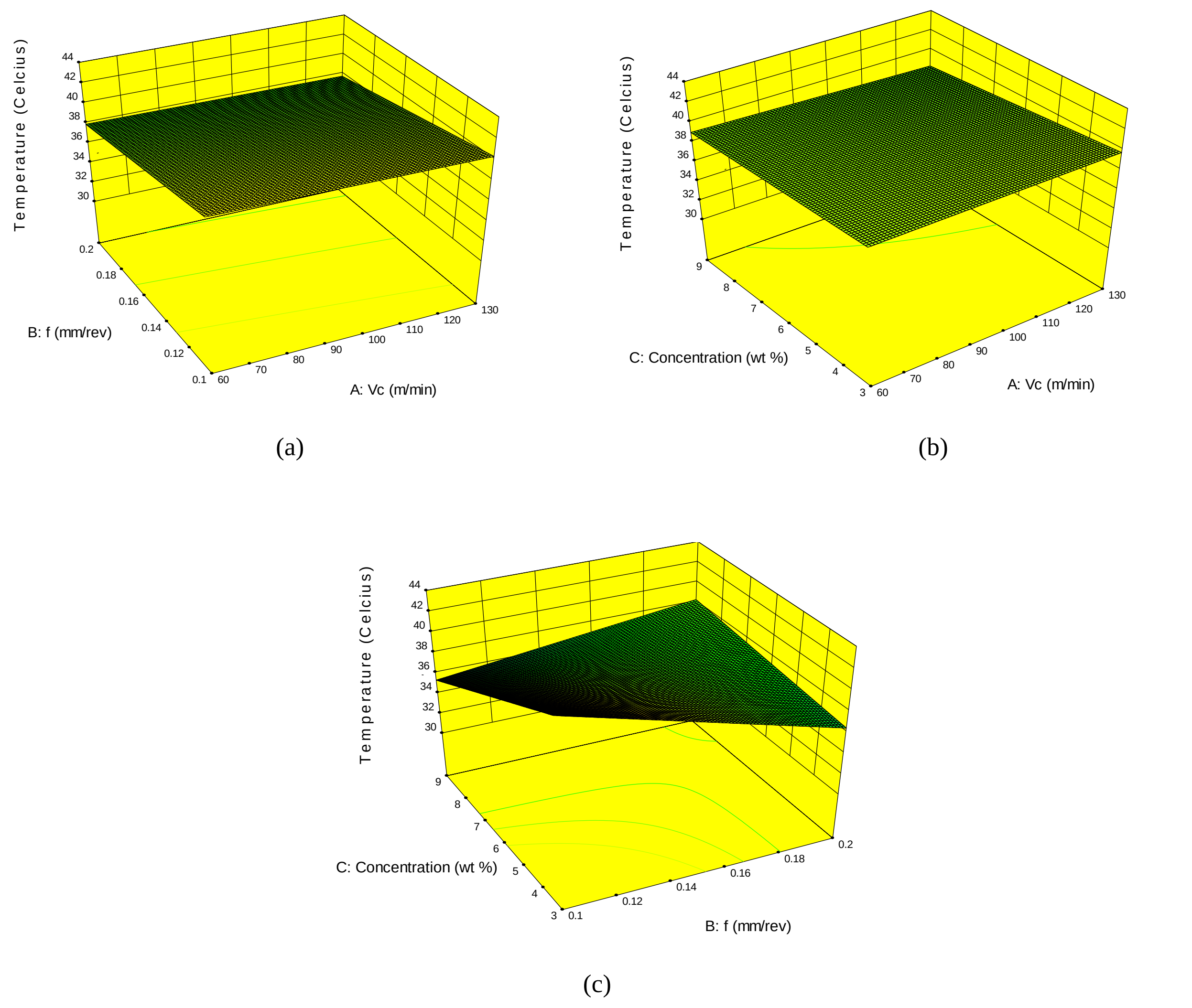
Fig. 5.1: Surface plots showing the variation of cutting force with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

The surface plots show that cutting force decreases with an increase in cutting velocity which is because increase in cutting velocity results in reduction of built up edge formation. The tool tip remains protected and does not wear out quickly. Thus, cutting force does not increase with increase in cutting velocity. Slight increase in cutting force is observed with increase in feed rate while increase in concentration of MoS_2 particles led to a significant reduction in cutting forces.

Increase in concentration of the cutting fluid by adding more MoS_2 particles increases the cooling and lubricating characteristics of the cutting fluid. This helps in reducing the cutting forces. The effect of different process parameters on cutting force was mathematically formulated into an equation as shown in equation 5.

$$Fz = 69.25 + (0.0354545 * Vc) + (327.333 * f) + (-1.21667 * C) + (-0.575758 * Vc * f) + (0.0151515 * Vc * C) + (-28.3333 * f * C) \quad (5)$$

Where, Fz denotes cutting force, f=feed rate, Vc= cutting velocity, C= concentration of MoS_2 particles in the cutting fluid.



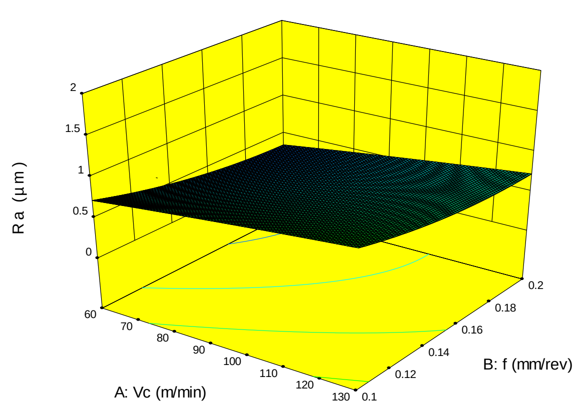
(a) (b) (c)

Fig. 5.2: Surface plots showing the variation of cutting temperature with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

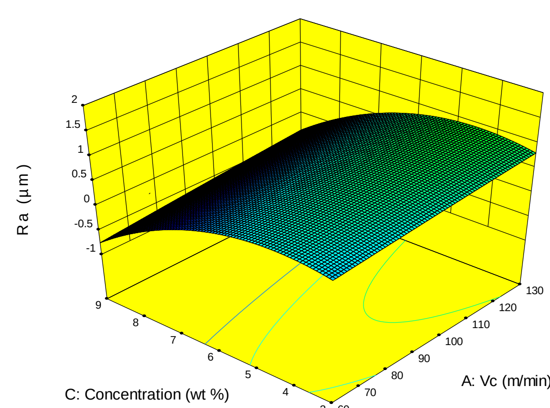
The surface plots of the variation of cutting temperature with respect to the process parameters show that cutting temperature increases with increase in cutting velocity. This is so because increase in cutting velocity increases the power consumption, hence more heat generation takes place which results in an increase in cutting tool temperature. Similarly with increase in feed rate, cutting tool temperature increases. The cutting temperature at the chip tool interface seems to decrease with increase in concentration of cutting fluid. This shows that addition of MoS_2 particles increases the heat dissipation capacity of the cutting fluid. Due to the small size of MoS_2 particles, the surface area to volume ratio of the powder increases which increase the heat dissipation capacity of the cutting fluid when MoS_2 particles are added. The combined effect of different process parameters on cutting zone temperature was mathematically formulated into an equation as shown in equation 6.

$$T = 58.9333 + (0.00333333 * Vc) + (-129.333 * f) + (-2.47778 * C) + (0.030303 * Vc * f) + (-0.0020202 * Vc * C) + (16.6667 * f * C) \qquad (6)$$

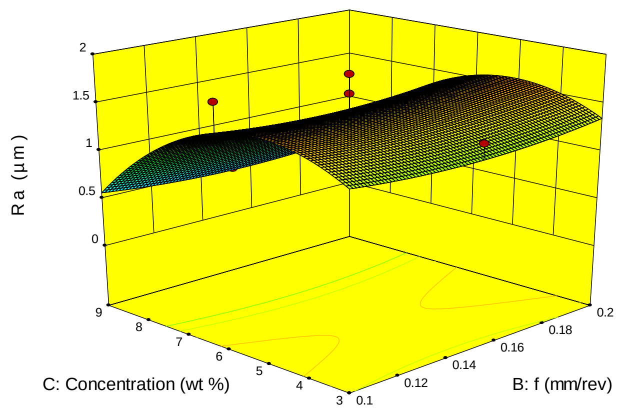
Where, T denotes cutting zone temperature, f=feed rate, Vc= cutting velocity, C= concentration of MoS_2 particles in the cutting fluid



(a)



(b)



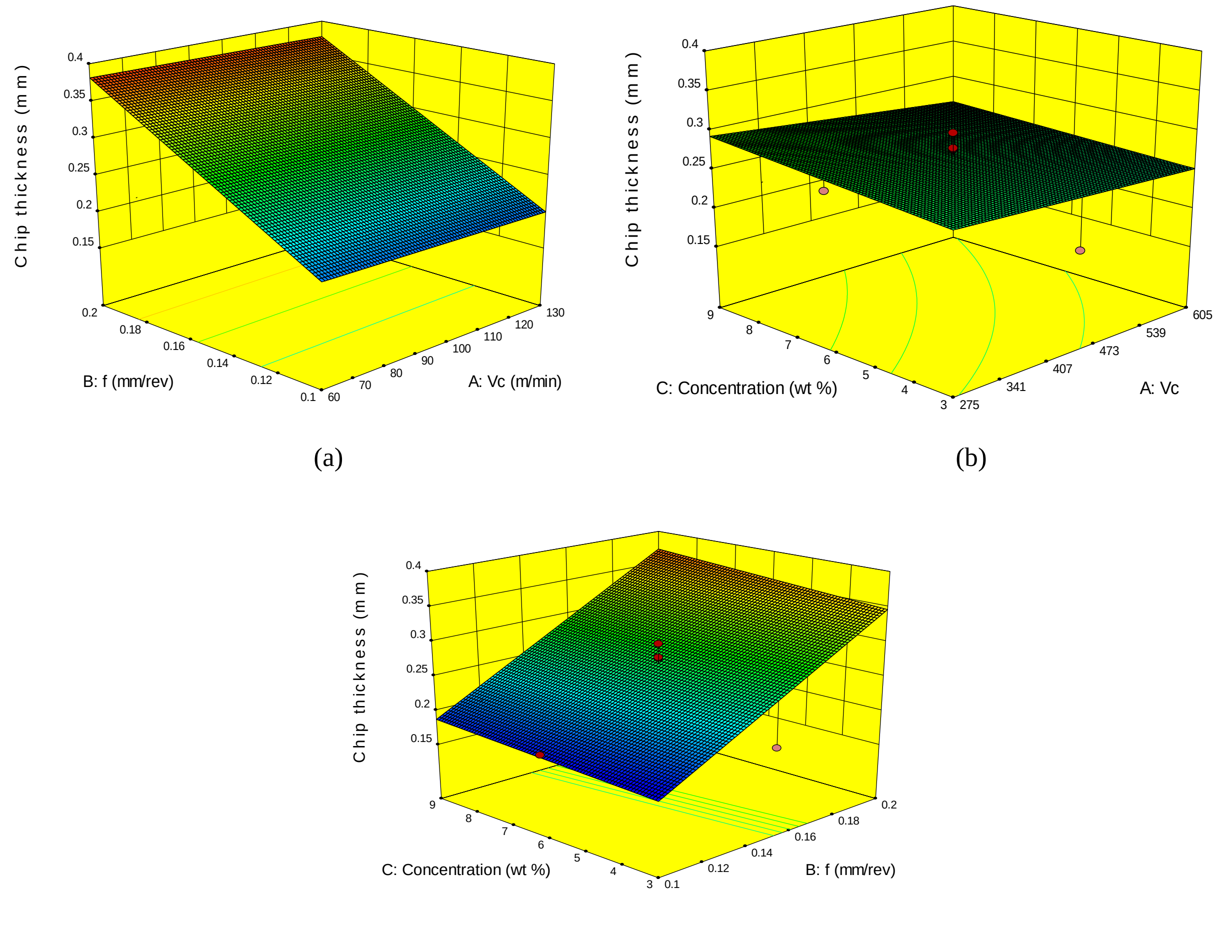
(c)

Fig. 5.3: Surface plots showing the variation of surface roughness with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

The variation of surface roughness with process parameters shows that increase in cutting velocity results in an increase in surface roughness. This is because increase in cutting velocity results in a higher heat generation which results in more thermal deformation of the tool material. Higher thermal deformation leads to more tool wear which directly affects the surface finish of the final workpiece. With increase in feed rate, the surface roughness increases. Surface roughness reduces significantly with an increase in concentration of the MoS_2 particles as is visible in Fig.5.2(c). This is due to the good lubricating properties of the MoS_2 particles which when added to the cutting fluid contribute in enhancing their properties in terms of reducing the coefficient of friction. The combined effect of different process parameters on surface roughness was mathematically formulated into an equation as shown in equation 7.

$$Ra = 0.570657 + (0.00352663 * Vc) + (-14.3303 * f) + (0.537348 * C) + (0.0106061 * Vc * f) + (0.000227273 * Vc * C) + (-0.0833333 * f * C) + (-7.84707e{-}006 * Vc^2) + (34.5455 * f^2) + (-0.0626263 * C^2) \quad (7)$$

Where, Ra denotes average surface roughness, f=feed rate, Vc= cutting velocity, C= concentration of MoS_2 particles in the cutting fluid



(a) (b) (c)

Fig. 5.4: Surface plots showing the variation of chip thickness with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

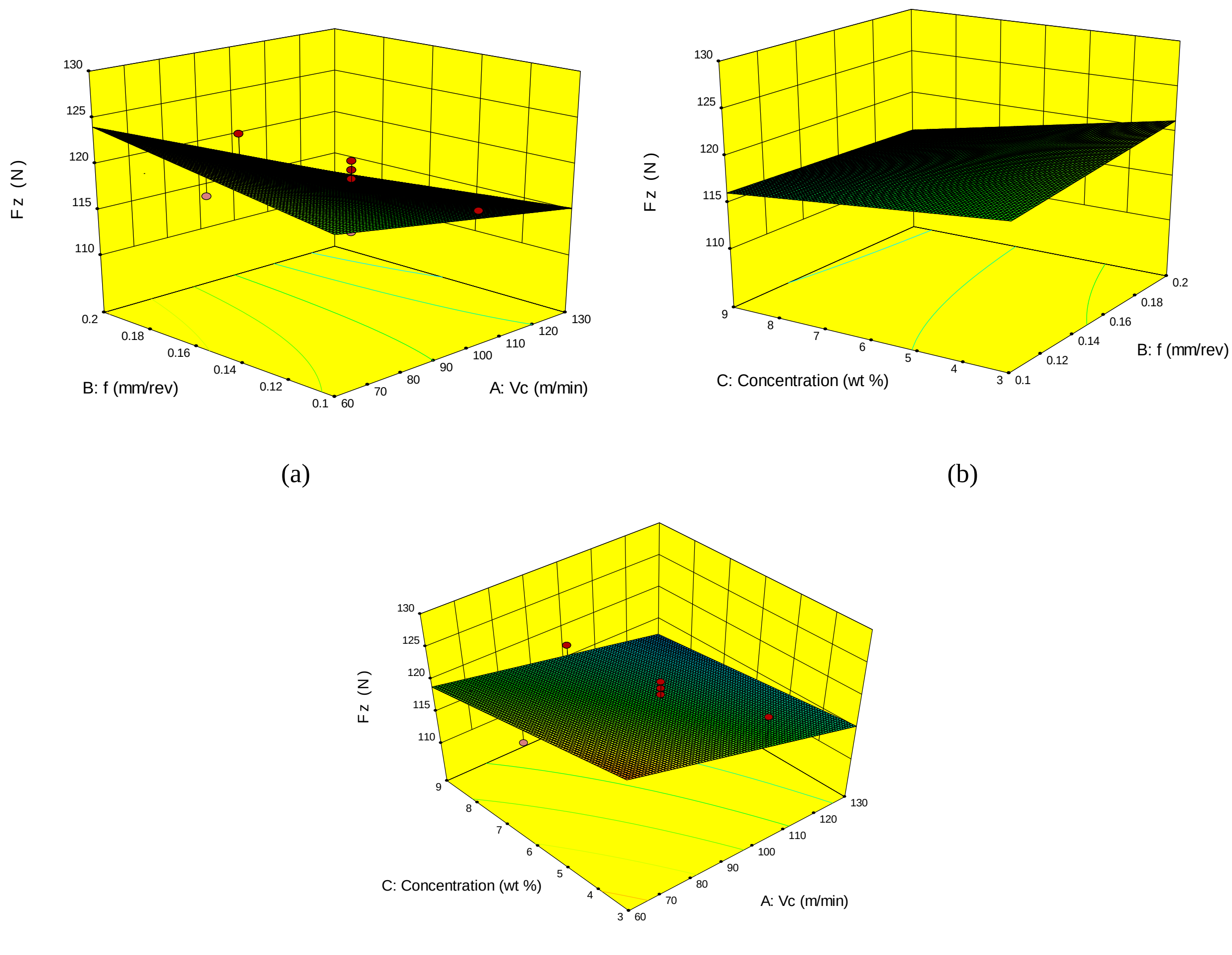
The study of chip thickness with respect to cutting velocity showed a slight increase in chip thickness with an increase in cutting velocity. This is because increase in cutting velocity leads to more power consumption and hence more heat generation. High heat produced causes thermal softening of the tool rake surface thus facilitating the chip to take off a thin layer of tool material along with it. This increases the chip thickness. Increase in feed also increases the chip thickness. With an increase in concentration of the cutting fluid, cutting zone temperature decreases which lessens the tendency of thermal distortion of the tool material thereby helping in restricting an increase in the chip thickness. The combined effect of different process parameters on surface roughness was mathematically formulated into an equation as shown in equation 8.

Chip thickness = 0.010905 + (-3.78636e-005 * Vc) + (1.65463 * f) + (0.00387861 * C) + (0.000101515 * Vc * f) + (-6.69192e-006 * Vc * C) + (0.01675 * f * C) (8)

Where, f=feed rate, Vc= cutting velocity, C= concentration of MoS_2 particles in the cutting fluid

5.1.2 Surface plots for the output responses obtained under the cutting environment of paraffin oil and MoS_2 based cutting fluid

Surface plots were generated for the output responses obtained under the cutting environment of paraffin oil mixed with MoS_2 particles. The combined effect of all the process parameters on cutting force is shown in Fig. 5.5 (a), (b) and (c).



(a) (b)

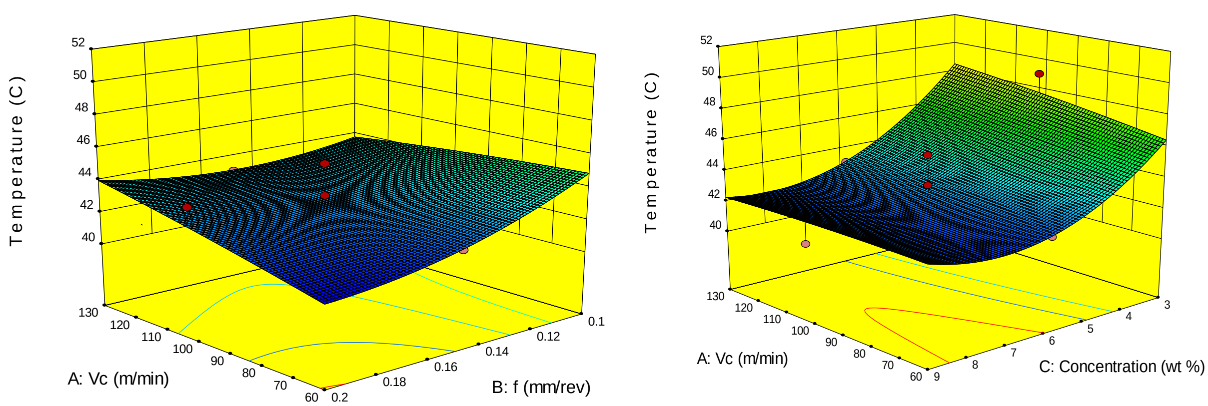
(c)

Fig. 5.5: Surface plots showing the variation of cutting force with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

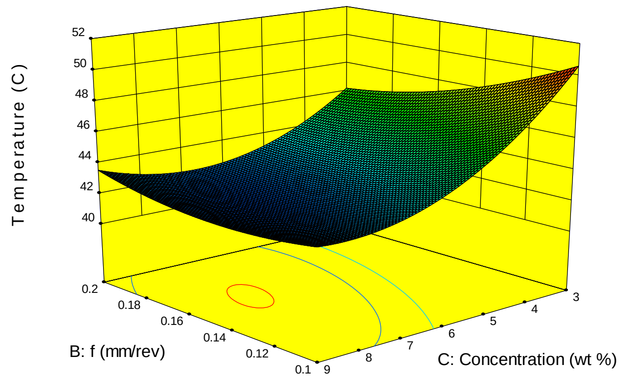
From the surface plots, it can be observed that cutting force increases with an increase in feed rate while there occurs a reduction in its value when cutting velocity is increased. This is quite obvious because as the cutting velocity is increased heat generation increases which softens the tool material thereby reducing force required for cutting. When the concentration of cutting fluid is increased, cutting forces reduce. This happens because addition of MoS_2 particles into the cutting fluid enhances the cooling and lubricating properties of the cutting fluid which reduces the cutting temperature and tool wear. This helps in reducing the cutting force. The combined effect of different process parameters on surface roughness was mathematically formulated into an equation as shown in equation 9.

$$Fz=116.928 + (-0.00581178 * Vc) + (132.439 * f) + (-0.587398 * C) + (-0.98374 * Vc * f) + (0.00663957 * Vc * C) + (-5 * f * C) \tag{9}$$

Where, Fz=cutting force, f=feed rate, Vc= cutting velocity, C= concentration of MoS_2 particles in the cutting fluid



(a) (b)



(c)

Fig. 5.6: Surface plots showing the variation of temperature with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

The analysis of the surface plots of temperature with respect to the process parameters shows that temperature increases with increase in cutting velocity and feed rate. However, the concentration of MoS_2 particles has got a significant effect on the cutting temperature. The cutting temperature reduces with increase in concentration of the cutting fluid. This is expected because addition of MoS_2 particles increases the heat dissipation capacity of the cutting fluid due to their large surface area to volume ratio. The combined effect of different process parameters on surface roughness was mathematically formulated into an equation as shown in equation 10.

$$T=78.1526 + (-0.0265693 * Vc) + (-223.548 * f) + (-4.70676 * C) + (0.597561 * Vc * f) + (-0.0052168 * Vc * C) + (8.33333 * f * C) + (-9.19913e-005 * Vc^2) + (327.273 * f^2) + (0.257576 * C^2) \quad (10)$$

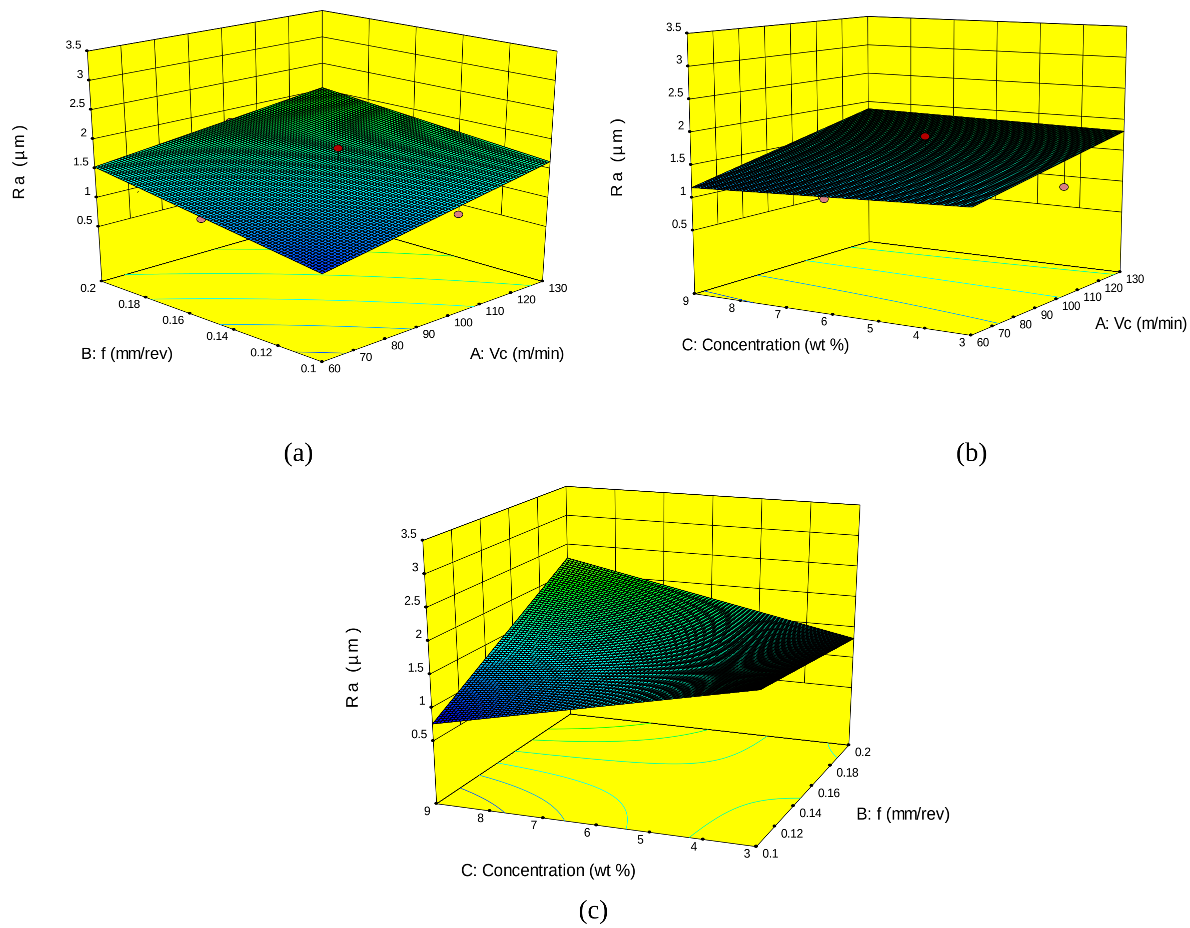
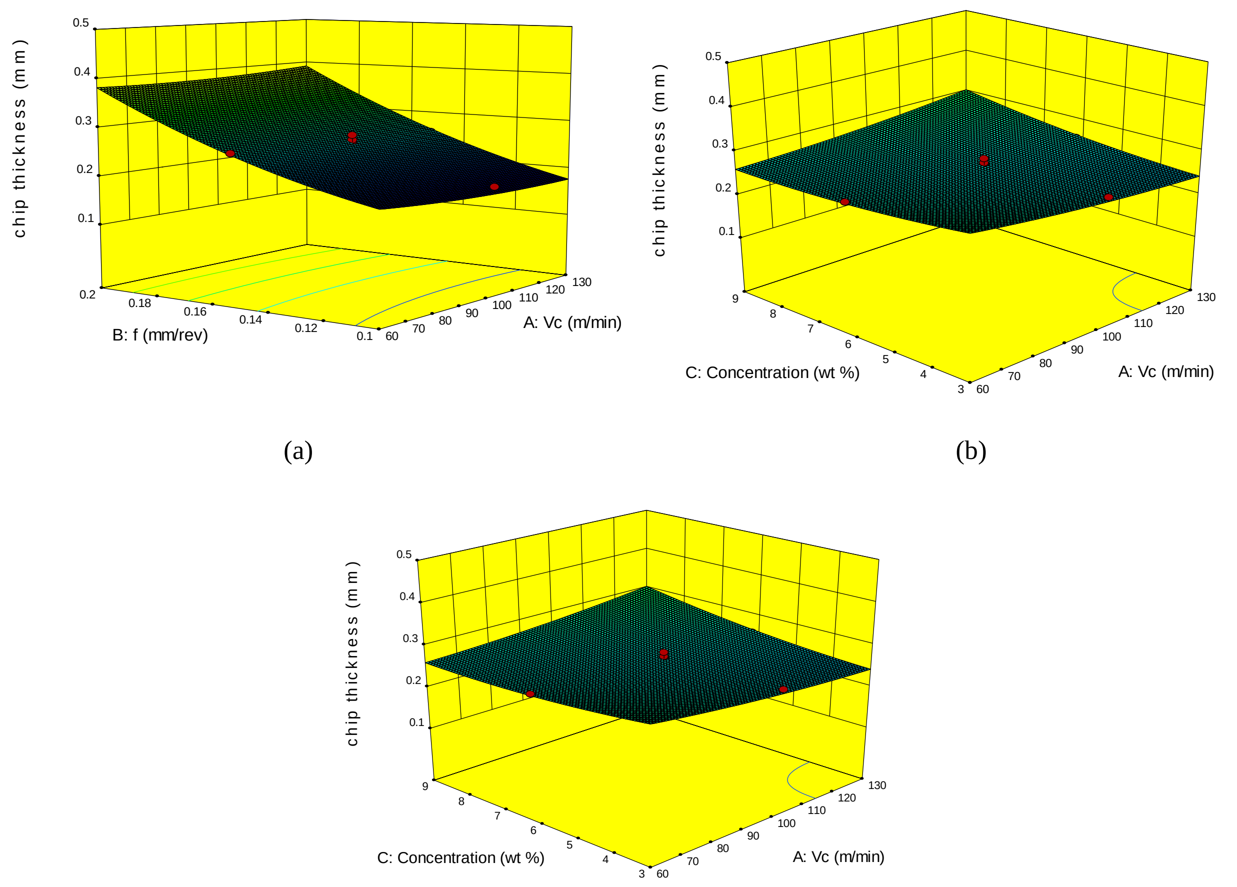


Fig. 5.7: Surface plots showing the variation of surface roughness with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

The interrelated effect of the process parameters on surface roughness as the output response was clearly depicted in the surface plots shown in Fig. 5.7 (a), (b) and (c). From the graphs it was observed that increase in cutting velocity and feed leads to an increase in the surface roughness. Large cutting velocities result in large heat generation which causes thermal damage to the tool tip. This deteriorates the surface finish. Increase in concentration of the cutting fluid results in a reduction of the surface roughness because of the lubricating effect of the MoS_2 particles. The combined effect of different process parameters on surface roughness was mathematically formulated into an equation as shown in equation 11.

$$Ra = 2.87369 + (0.00982459 * Vc) + (-12.1463 * f) + (-0.556098 * C) + (-0.0276423 * Vc * f) + (0.000514905 * Vc * C) + (3.33333 * f * C)$$



(a) (b) (c)

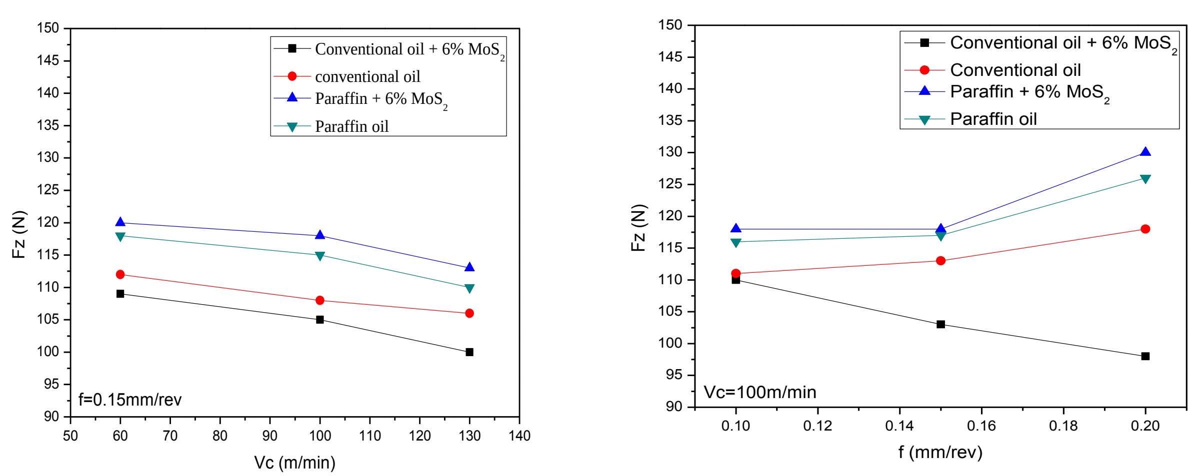
Fig. 5.8: Surface plots showing the variation of surface roughness with respect to the combined effect of (a) Vc and f (b) Vc and C (c) f and C

Fig. 5.8 shows the variation of chip thickness with respect to the process parameters involved in the machining process. From the plots it can be observed that with an increase in cutting velocity and feed rate, chip thickness increases while increase in concentration of the cutting fluid helps in slight reduction of the chip thickness. Increase in concentration of MoS_2 particles increase thermal dissipation capacity of the cutting fluid thereby reducing the chip tool interface temperature. This prevents the chip from adhering to the tool rake surface. Thus, there occurs less adhesion of the tool material on the undersurface of the chips which restricts an increase in the chip thickness. The combined effect of different process parameters on surface roughness was mathematically formulated into an equation as shown in equation 12.

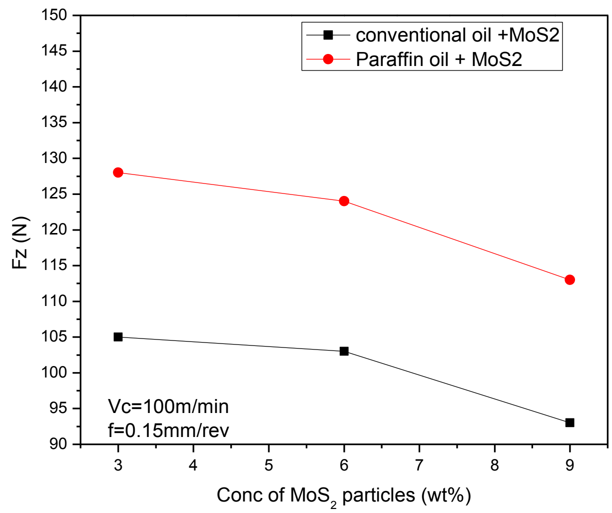
Chip thickness = 0.4786 + (-0.00289976 * Vc) + (-1.32288 * f) + (-0.0472716 * C) + (0.00349472 * Vc * f) + (0.000218909 * Vc * C) + (0.10525 * f * C) + (5.39448e-006 * Vc^2) + (7.98364 * f^2) + (0.00111212 * C^2)

5.2 Comparative evaluation of different MQL environments on machinability characteristics of austenitic stainless steel 316L

For a justified comparison, the output responses for each environment were plotted against a varying process parameter while keeping the other two parameters constant. The output responses under consideration were cutting force, cutting temperature, surface roughness and chip thickness. Thus, for each output response, effect of each process parameter was studied under all the lubricating environments. The plots for each parametric effect on cutting force under all the four lubricating conditions are shown in Fig. 5.9 (a), (b) and (c).



(a) (b)

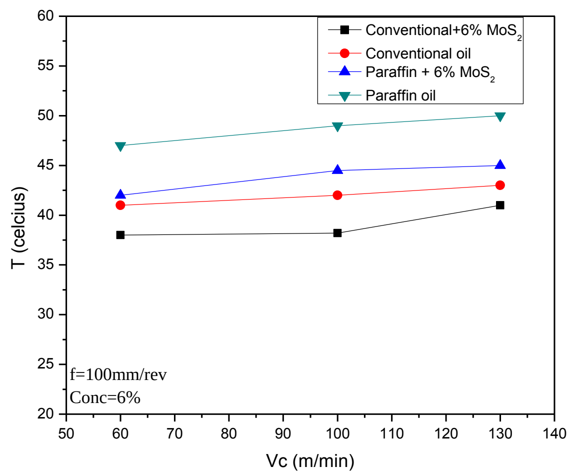


(c)

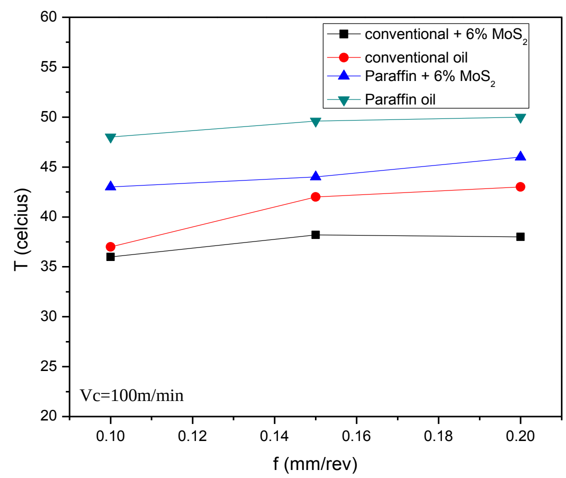
Fig. 5.9: Plots showing the variation of cutting force with respect to (a) cutting velocity ‘Vc’, (b) feed ‘f’ and (c) concentration of MoS_2 particles under all the lubricating environments

The cutting force is an important parameter which significantly affects the performance of any cutting process. Thus, variation of cutting force with respect to the process parameters is explored thoroughly by plotting the values against all the parameters (Vc, f and concentration of MoS_2 particles).The plot of Fz vs Vc shows that in general cutting force reduces slightly with an increase in the cutting velocity under all the cutting environments. This is because with an increase in cutting velocity, more heat is generated which causes thermal softening of the tool material thereby reducing the cutting force. Further, it is observed from the plot that highest cutting force is obtained in the environment of MoS_2 mixed paraffin oil followed by paraffin oil as the cutting fluid. This is because paraffin oil has got lower heat capacity as compared to water based conventional cutting fluid. Thus, cutting fluids with paraffin oil as the base fluid possess lower heat dissipation capacity. Lower reduction in cutting temperature leads to an increase in thermal softening. Due to thermal softening of the tool, cutting forces reduce. Conventional oil based cutting fluid, mixed with MoS_2 has maximum heat dissipation capacity due to the combined effect of cooling capacity of water and MoS_2. This causes least thermal distortion and hence lowest amount of tool wear. Since the tool does not get worn out, cutting forces reduce. A similar trend is observed for the variation of cutting forces with respect to feed rate. Cutting forces increase with an increase in feed rate but least cutting force is observed for MoS_2 mixed conventional oil. The study of the effect of concentration of MoS_2 particles on the cutting forces showed that there is a continuous reduction in cutting forces with an increase in its concentration. This is because increase in concentration provides an increased cooling effect which reduces the magnitude of cutting force.

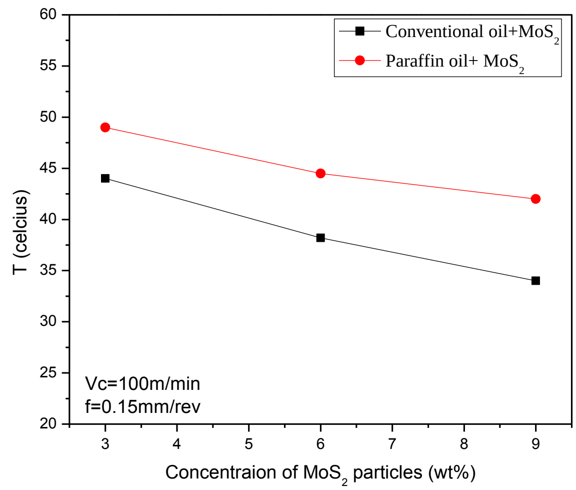
The plots for each parametric effect on cutting temperature under all the four lubricating conditions are shown in Fig. 5.10 (a), (b) and (c).



(a)



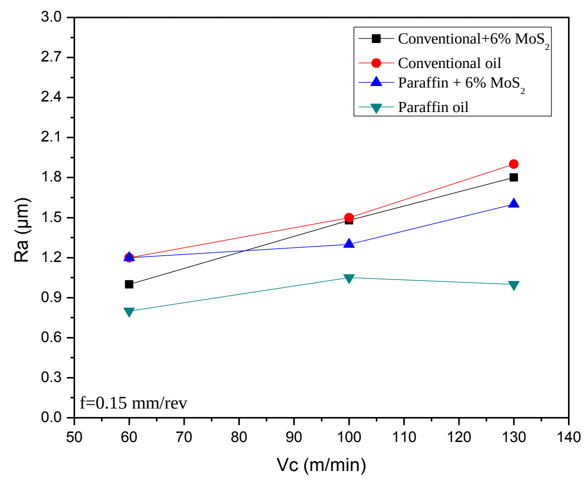
(b)



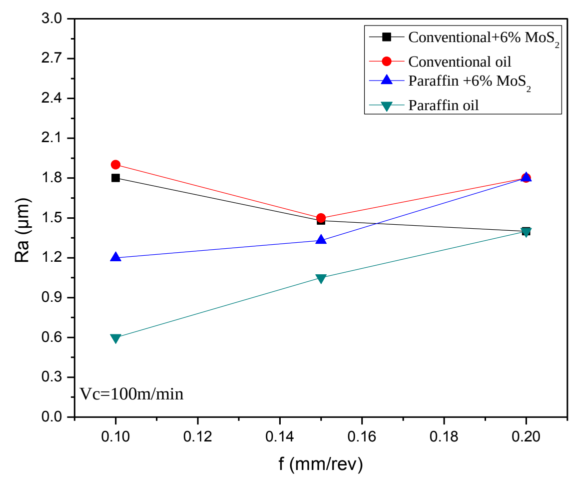
(c)

Fig. 5.10: Plots showing the variation of cutting temperature with respect to (a) cutting velocity 'Vc', (b) feed 'f' and (c) concentration of MoS_2 particles under all the lubricating environments

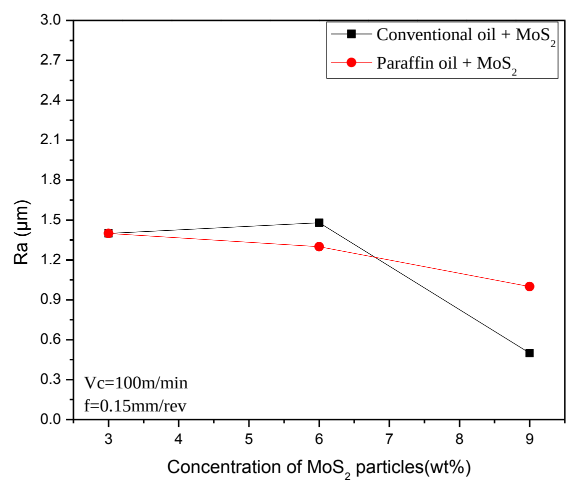
The plot of cutting zone temperature with respect to cutting velocity shows a slight increase in the cutting temperature with a corresponding increase in the cutting velocity. This is because as the cutting velocity increases, power consumption increases which increases the amount of heat generated. The increase in heat generation leads to an increase in the cutting zone temperature. One of the primary functions of any cutting fluid is to lower down this temperature as much as possible so as to prevent thermal deformation and built up edge formation. In all the cutting fluids under consideration, it is observed that lowest temperature is measured for conventional fluid with MoS_2 particles. Since, the conventional fluid is water soluble and it is prepared by mixing 2 volumes of water and 1 volume of cutting fluid, so large temperature reduction is possible because of the cooling capacity of water present in the conventional fluid. This cutting fluid has got an extra advantage of the presence of MoS_2 particles which due to their large surface area to volume ratio have got an excellent heat dissipation capacity. Thus, the combined effect of water and MoS_2 particles leads to a significant amount of temperature reduction. Similarly, the variation of cutting zone temperature with respect to feed rate shows a slight increase in the values with lowest values observed for the cutting environment of conventional fluid and MoS_2 particles. The comparison of MoS_2 based paraffin oil and conventional oil shows that lower values of temperature are recorded for the later environment. This is because conventional oil has got an extra advantage of the presence of water which has got higher specific heat capacity (4.186 J/g °C)as compared to paraffin oil (2.13 J/g°C)due to which the capacity to take away heat from the cutting zone increases for the water based conventional fluid. The plots for each parametric effect on cutting force under all the four lubricating conditions are shown in Fig. 5.11 (a), (b) and (c).



(a)



(b)

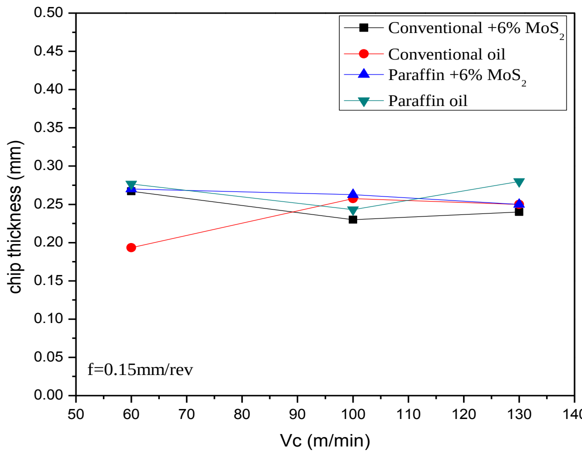


(c)

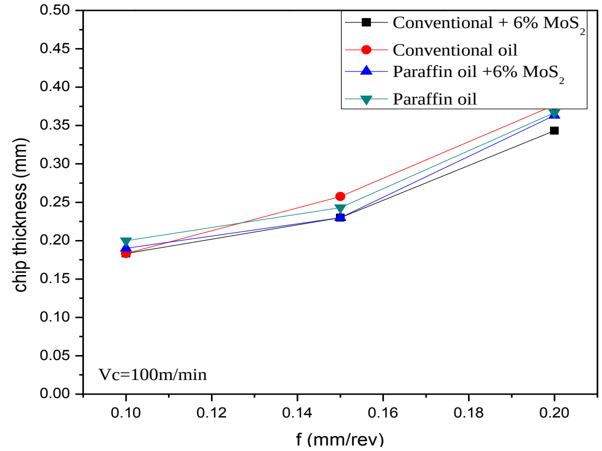
Fig. 5.11: Plots showing the variation of surface roughness with respect to (a) cutting velocity 'Vc', (b) feed 'f' and (c) concentration of MoS_2 particles under all the lubricating environments

The analysis of surface roughness of the machined workpiece under different machining environments indicated that best surface finish was obtained for the machining under paraffin oil. The lower values of surface roughness obtained for paraffin oil based cutting fluids establish the fact that in general paraffin oil has got better lubricating properties as a fluid than the conventional cutting fluid. Addition of MoS_2 particles in the conventional fluid reduces the surface roughness slightly. This is because of the solid lubricant properties of MoS_2 particles which add to the lubricating properties of the cutting fluid. However, when MoS_2 particles are mixed in paraffin oil, the surface finish could not be improved. This may be because high viscosity of paraffin oil mixed with MoS_2 particles might have reduced the flowability of the cutting fluid which prevented it from entering into the cutting zone. Thus, the effect of adding MoS_2 particles could not be properly established. However, if the particle size is reduced further, the chances of improvement in surface finish might open up in case of paraffin oil as the base fluid. Similar variation in the surface roughness is observed with variation in feed rate keeping other two parameters constant. The variation of surface roughness with change in concentration of cutting fluid shows that as the concentration of MoS_2 particles is increased, surface roughness on an average reduces in both the cutting fluids. However, this reduction is more prominent in case of MoS_2 mixed conventional oil than that of paraffin oil. This may be due to a similar observation as before. The high viscosity of paraffin oil mixed with MoS_2 might have obstructed the flow of the fluid into the cutting zone which caused a lesser improvement in surface finish.

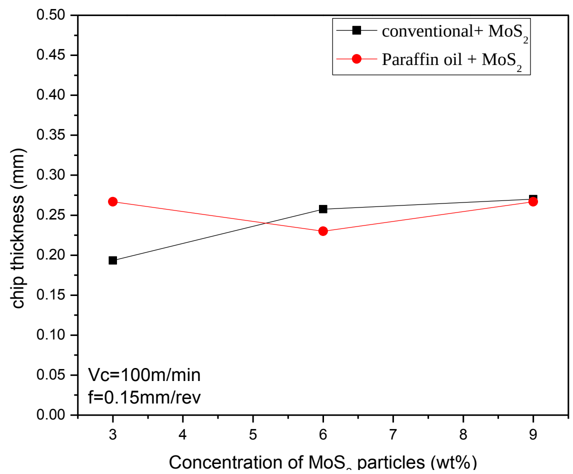
The plots for each parametric effect on cutting force under all the four lubricating conditions are shown in Fig. 5.12 (a), (b) and (c).



(a)



(b)



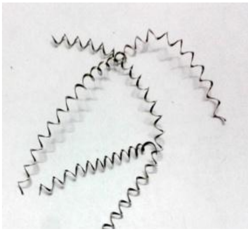
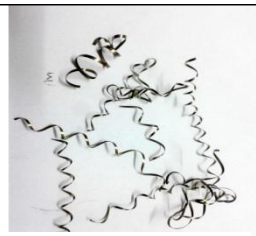
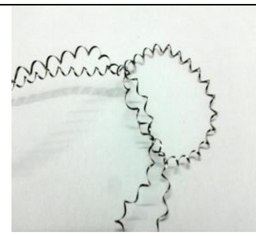
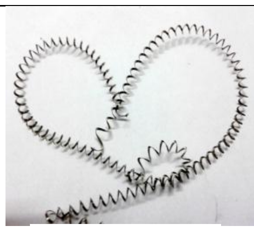
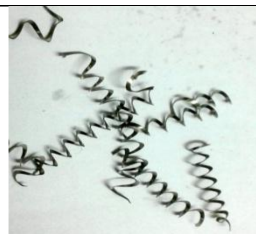
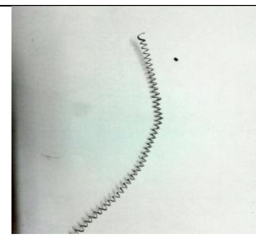
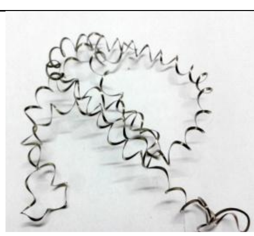
(c)

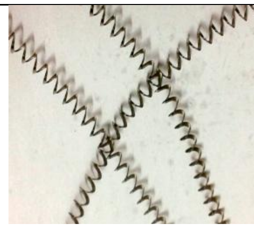
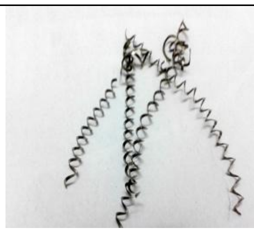
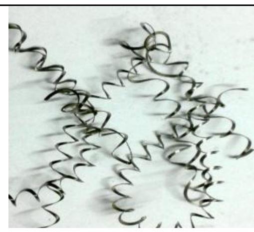
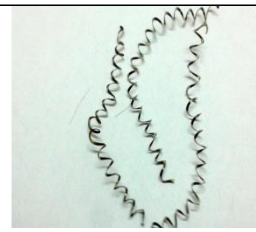
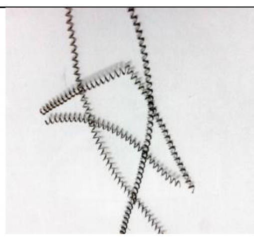
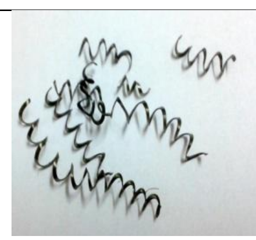
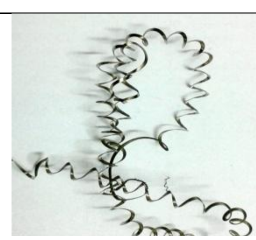
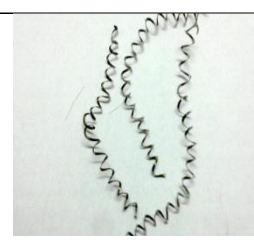
Fig. 5.12: Plots showing the variation of chip thickness with respect to (a) cutting velocity 'Vc', (b) feed 'f' and (c) concentration of MoS_2 particles under all the lubricating environments

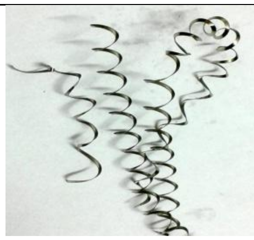
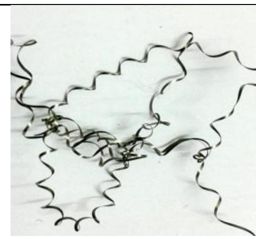
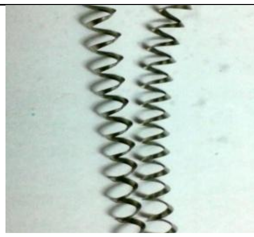
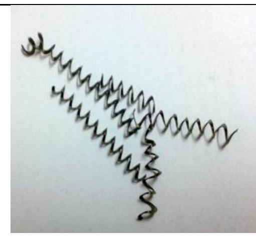
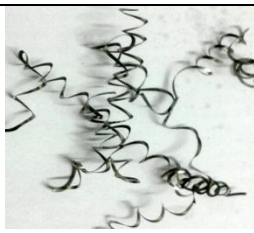
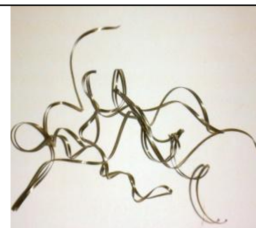
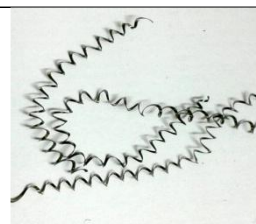
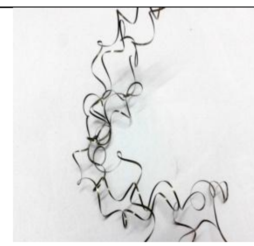
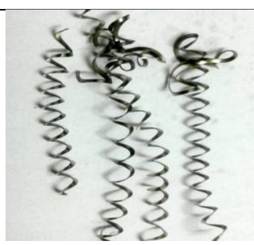
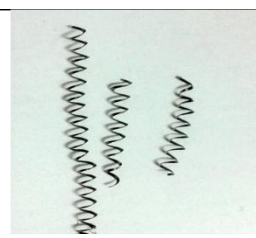
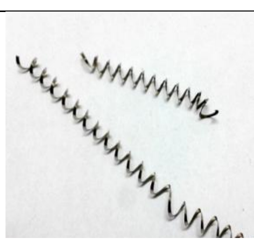
The variation of chip thickness with cutting velocity shows that, with an increase in cutting velocity there is a slight reduction in chip thickness. This may be attributed to the fact that due to an increase in cutting velocity, the adhesion tendency at the chip tool interface reduces. This causes lesser material from the tool to stick to the chip surface. Thus, chip thickness appears to get reduced with an increase in cutting velocity. It was observed that, least value of chip thickness was obtained for MoS_2 mixed conventional cutting fluid. This is because the addition of MoS_2 in the conventional cutting fluid as well as the presence of water causes a significant reduction in cutting temperature. Due to this, no thermal distortion takes place at the chip tool interface and no adhesion occurs. Thus, chip thickness is less as compared to that obtained under other cutting environments. Since, paraffin oil has got lower heat dissipating capacity as compared to the other cutting fluids, chip thickness obtained under this cutting environment is high. Addition of MoS_2 particles in the cutting fluid assist in reducing the cutting zone temperature thus reducing the chip thickness because lesser sticking takes place at the chip tool interface. The variation in chip thickness with respect to concentration of the cutting fluid shows that at low concentration, chip thickness was high for paraffin oil. This is because at low concentration of MoS_2 particles, higher cutting temperatures were generated. Low concentration of MoS_2 was not sufficient to reduce the chip thickness significantly. However, with an increase in the concentration of MoS_2 particles, the detrimental effect of high cutting temperature due to paraffin oil could be significantly restricted by the enhanced heat transfer characteristics of MoS_2 particles. Too much concentration of MoS_2 particles results in hindrance in chip flow causing stagnancy which further leads to an increasing trend in the chip thickness. Thus, it can be concluded that if conventional oil is used as the cutting fluid then 3% should be the optimal concentration to reduce chip thickness and if paraffin oil is used as the cutting fluid, then 6% should be considered as the optimal parameter.

5.3 Study of chip morphology

After performing each experimental run, chips were collected for further examination. The images of the chips collected for each run were taken and tabulated as shown in Fig. 5.13.

Run no.	Conventional oil + MoS_2	Conventional oil	Paraffin oil+ MoS_2	Paraffin oil
1	 Continuous	 Continuous	 Continuous	 Discontinuous
2	 Continuous	 Continuous	 Continuous	 Continuous
3	 Long spiral	 Continuous	 Long spiral	 Discontinuous
4	 Long spiral	 Long spiral	 Discontinuous	 Discontinuous
5	 Continuous	 Continuous	 Continuous	 Continuous

6	 Continuous	 Continuous	 Continuous	 Continuous
7	 Long spiral	 Long spiral	 Broken fragments	 Discontinuous
8	 Continuous	 Continuous	 Continuous	 Continuous
9	 Long spiral	 Continuous	 Continuous	 Continuous wavy
10	 Long spiral	 Long spiral	 Continuous	 Short Continuous
11	 Continuous	 Continuous	 Continuous	 Continuous

12	 Continuous	 Continuous wavy	 Continuous wavy	 Continuous wavy
13	 Long tubular	 Continuous	 Continuous	 Continuous broken
14	 Continuous wavy	 Continuous	 Continuous wavy	 Continuous wavy
15	 Continuous	 Continuous	 Continuous	 Continuous wavy
16	 Continuous	 Continuous	 Continuous tubular	 Continuous helix
17	 Long continuous	 Continuous	 Continuous	 Continuous

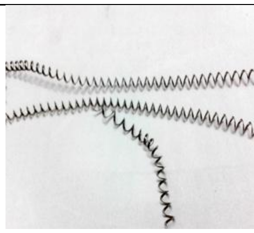
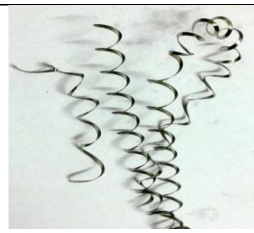
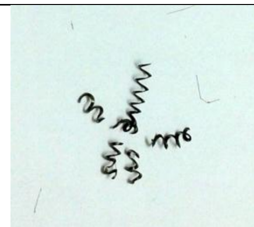
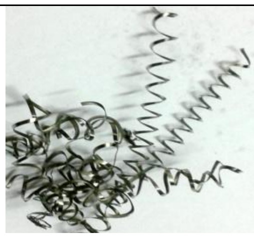
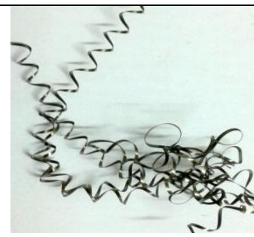
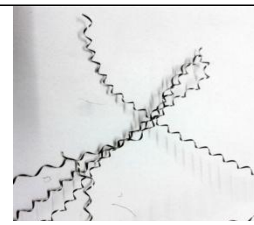
18	 Long helical	 Long spiral	 Long continuous	 Long continuous
19	 Long helical	 Continuous	 Discontinuous	 Discontinuous
20	 Continuous	 Continuous	 Continuous	 Long wavy

Fig. 5.13: Images of chips formed under different cutting environments

It was found from visual inspection that mostly continuous chips were obtained for machining under conventional fluid. Addition of MoS_2 particles in the conventional fluid led to a reduction in the helix angle of the chip which can be seen as closely coiled chips in this environment. This was because in case of MoS_2 mixed cutting fluid, the impingement of the particles might have caused the chips to curl more. The observations further showed that more discontinuous chips were obtained for machining under paraffin oil as the base cutting fluid. Because of good lubricating properties of paraffin oil, it does not allow the chips to form in continuous ribbon like manner. Therefore, application of paraffin oil leads to reduction in chip curl radius and also effective segmentation of chip due to flowing of fluid in the chip tool interface. Even under some conditions where continuous chips are formed, chips with lower curl radius were observed.

5.4 Grey relational analysis (GRA) of MoS_2 mixed conventional oil as the cutting fluid

From the analysis of the above graphs, it is quite clear that the environment consisting of MoS_2 mixed conventional oil is producing better results in terms of minimizing the cutting temperatures, cutting forces, and chip thickness. Thus, our further focus will be on the cutting environment of conventional oil and MoS_2 particles. The response table for this cutting environment is as shown in Table 5.5.

Table 5.5: Response table for cutting environment of MoS_2 particles mixed with conventional oil

Run no	Vc (m/min)	f (mm/rev)	Concentration of MoS_2 particles (wt%)	Fz (N)	T (ºC)	Ra (µm)	Chip thickness (mm)
1	130	0.20	9	106	34	0.4	0.2667
2	100	0.15	6	105	39	1.4	0.1933
3	100	0.15	6	104	36	1.4	0.2667
4	100	0.15	6	106	40	1.2	0.3433
5	100	0.15	6	105	36	0.8	0.1800
6	130	0.20	3	101	35	1.0	0.2700
7	100	0.15	6	104	40	1.8	0.3733
8	100	0.20	6	108	38	1.4	0.2773
9	60	0.20	3	110	35	1.3	0.3667
10	100	0.10	6	104	36	1.8	0.2033
11	100	0.15	9	106	34	0.5	0.1967
12	130	0.10	3	99	42	0.6	0.2786
13	60	0.20	9	107	38	0.4	0.2981
14	100	0.15	6	105	40	1.6	0.3933
15	100	0.15	3	106	44	1.4	0.2453
16	130	0.10	9	100	31	0.2	0.2775
17	60	0.10	3	110	43	1.4	0.1833
18	60	0.10	9	106	36	0.4	0.2430
19	60	0.15	6	109	38	1.0	0.3633
20	130	0.15	6	100	41	1.8	0.1767

After measuring the responses, each response value was normalized in accordance with the equation 1. The normalized values of the responses are tabulated in Table 5.6.

Table 5.6: Normalised sequence of the output responses

Run no.	Fz (N)	T (ºC)	Ra (μm)	Chip thickness (mm)
1	0.759259	0.769231	0.8750	0.584488
2	0.777778	0.384615	0.2500	0.923361
3	0.796296	0.615385	0.2500	0.584488
4	0.759259	0.307692	0.3750	0.23084
5	0.777778	0.615385	0.6250	0.984765
6	0.851852	0.692308	0.5000	0.569252
7	0.796296	0.307692	0	0.092336
8	0.722222	0.461538	0.2500	0.535549
9	0.685185	0.692308	0.3125	0.122807
10	0.796296	0.615385	0	0.877193
11	0.759259	0.769231	0.8125	0.907664
12	0.888889	0.153846	0.7500	0.529548
13	0.740741	0.461538	0.8750	0.43952
14	0.777778	0.307692	0.1250	0
15	0.759259	0	0.2500	0.683287
16	0.870370	1.0000000	1.0000	0.534626
17	0.685185	0.076923	0.2500	0.969529
18	0.759259	0.615385	0.8750	0.693906
19	0.703704	0.461538	0.5000	0.138504
20	0.870370	0.230769	0	1.000000

Followed by formulating the normalized sequences, the grey relational coefficients and grey relational grade are evaluated using the equations 2 and 3. The corresponding values are tabulated in Table 5.7. The grey relational grades are then ranked in accordance with their values. Highest value of grade is given rank 1 and so on. The combination of process parameters which give highest value of grey relational grade is considered to be the optimal set of parameters.

Table 5.7: Grey relational coefficients and grey relational grades of the normalized sequence of output responses

Run no.	Fz (N)	T (ºC)	Ra (μm)	Chip thickness (mm)	Grey relational grade	Rank
	Grey relational coefficients					
1	0.397059	0.393939	0.363636	0.461047	0.40392	18
2	0.391304	0.565217	0.666667	0.351281	0.493617	12
3	0.385714	0.448276	0.666667	0.461047	0.490426	13
4	0.397059	0.619048	0.571429	0.684144	0.56792	6
5	0.391304	0.448276	0.444444	0.336754	0.405195	17
6	0.369863	0.419355	0.500000	0.467617	0.439209	15
7*	0.385714	0.619048	1.00000	0.844115	0.712219	1
8	0.409091	0.520000	0.666667	0.482835	0.519648	10
9	0.421875	0.419355	0.615385	0.802817	0.564858	7
10	0.385714	0.448276	1.00000	0.363057	0.549262	9
11	0.397059	0.393939	0.380952	0.355198	0.381787	19
12	0.36000	0.764706	0.400000	0.48565	0.502589	11
13	0.402985	0.520000	0.363636	0.532187	0.454702	14
14	0.391304	0.619048	0.800000	1.000000	0.702588	2
15	0.397059	1.000000	0.666667	0.422552	0.621569	3
16	0.364865	0.333333	0.333333	0.483266	0.378699	20
17	0.421875	0.866667	0.666667	0.340245	0.573863	5
18	0.397059	0.448276	0.363636	0.418794	0.406941	16
19	0.415385	0.520000	0.500000	0.783080	0.554616	8
20	0.364865	0.684211	1.00000	0.333333	0.595602	4

* Run no. corresponding to optimal set of process parameters

From the evaluation of grey relational grades and their ranking, it is quite clear that highest grey relational grade is obtained for run no. 7, i.e. for Vc = 100m/min, f = 0.15mm/rev and concentration of MoS_2 particles as 6% as shown in Fig. 5.14. The output responses corresponding to this set of process parameters is Fz=104N, T=40ºC, Ra=1.8 μm, chip thickness=0.3733mm.

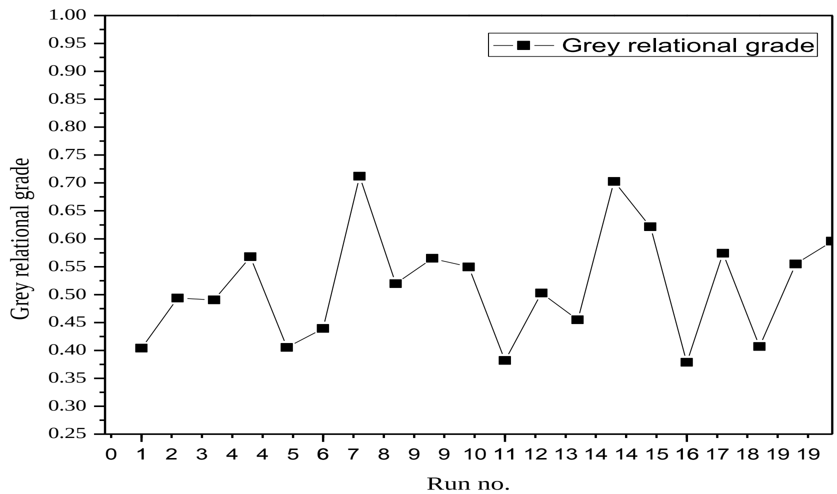


Fig.5.14: Variation of Grey relational grade with run number

After determining the optimal set of process parameters using grey relational analysis, final step is to perform actual experiments corresponding to the same set of optimal parameters so as to validate the results obtained. However, it was observed that from the design of experiments that the combination of process parameters corresponding to the optimal set had already been performed 6 times. Thus, confirmation tests were not carried out again to avoid the replication of results. The mean values of the output responses were calculated from the response table as shown in Table 5.8 which have a close approximation with the results obtained from the optimal set of parameters obtained through grey relational analysis.

Table 5.8: Response table for the confirmatory test

Optimal parametric combination	Average cutting force (N)	Average temperature (ºC)	Average surface Roughness (µm)	Average chip thickness (mm)
Vc=100m/min , f=0.15mm/rev C = 6% by wt.	104.833	38.5	1.367	0.29165

CHAPTER 6
CONCLUSIONS

The current research work was carried out to study the effect of MQL with different cutting environments consisting of paraffin oil and conventional water soluble cutting oil, each mixed with MoS_2 powder on the machinability characteristics of austenitic stainless steel AISI 316L. The interrelated effect of process parameters on the output responses (cutting force, surface roughness, cutting temperature and chip thickness) were studied thoroughly with the help of surface plots based on response surface methodology. A comparative study of the effect of addition of MoS_2 particles in the cutting fluid was carried out and the variation of the output responses with respect to the process parameters was analyzed. Once it was observed that MoS_2-mixed conventional cutting fluid exhibited favourable machining performance, further attempt was made to determine optimal cutting condition using grey relational analysis. Based on the observations and analysis, following conclusions can be drawn:

1. The parametric effect on the output responses showed that cutting forces decreased with increase in cutting velocity and increased with feed. Addition of MoS_2 particles helped in reducing the cutting forces.
2. Increase in cutting velocity and feed rate resulted in an increase in cutting temperature, while mixing of MoS_2 powder in both the cutting oils contributed in reduction in cutting temperature. Increase in concentration of MoS_2 particles also led to reduction in cutting temperature.
3. Surface roughness increased with increase in cutting velocity and feed rate while increasing the concentration of MoS_2 particles assisted in improving the surface finish.

4. Study of chip morphology indicated that continuous helical chips were mostly obtained under most of the cutting conditions, while machining under paraffin oil generated segmented chips or continuous chips with less curl radius. Addition of MoS_2 particles in the cutting fluids led to a reduction in the chip helix angle such that closely helical chips were formed.
5. Chip thickness increased with increase in cutting velocity and feed rate while addition of MoS_2 with optimal concentration (3% for conventional cutting fluid and 6% for paraffin oil) appeared to restrict the increase of chip thickness.
6. The cutting environment of conventional fluid mixed with MoS_2 particles helped in considerable reduction in the cutting force. Increase in concentration of MoS_2 also resulted in reduction in cutting force.
7. Higher cutting temperature was observed for paraffin oil as compared to conventional water soluble cutting oil. Addition of MoS_2 powder restricted the increase in temperature for both the base fluids. However, the study established conventional cutting fluid as a better coolant than paraffin oil.
8. Better surface finish was obtained for machining under paraffin oil as the cutting fluid or even when it was mixed with MoS_2 particles when compared to that obtained under MQL with conventional fluid. This indicates that paraffin oil has got better lubricating properties than conventional cutting fluid.
9. Addition of MoS_2 particles in paraffin oil could not help in enhancing its lubricating properties. Minimum chip thickness was obtained during machining under conventional cutting fluid mixed with MoS_2 particles.

10. Optimization of the process parameters for machining under the environment of cutting fluid mixed with MoS_2 particles resulted in the optimal parametric combination as Vc=100m/min, f=0.15mm/rev and C=6% by weight.

6.1. Contribution of the research work

The current research work demonstrated and established the effectiveness of machining AISI 316L austenitic stainless steel under MQL with MoS_2 powder-mixed cutting fluid. The effect of two different base fluids namely conventional water soluble cutting oil and paraffin oil has also been investigated. Significant reduction obtained in cutting temperature along with decrease in surface roughness, cutting force and chip thickness when MoS_2 powder was added to the base fluid clearly exhibited the supremacy of powder- mixed MQL in turning operation. The outcome thus obtained from the current study is expected to be of immense significance for various machining industries.

6.2. Recommendation and future scope of research

The present investigation indicated MoS_2 powder-mixed possesses the capability to significantly augment cooling ability of cutting fluid. The contribution of same MoS_2 powder in improving the lubrication effect was found to be little less compared to the cooling effect. Therefore, MoS_2 powder-mixed MQL would be highly recommended for the application where cooling is more stringent requirement compared to lubrication effect for example for machining materials with low thermal conductivity like stainless steel, titanium alloy or nickel-based super alloys.

Future endeavour should be made to further research work in the field of powder-mixed MQL

1. Influence of particle size of the powder from micron to nano metric range should be evaluated on various machining characteristics.
2. Effect of MoS_2 powder-mixed MQL should be studied on tool wear characteristics

3. Performance of MoS_2 powder with other powders like graphite, Al_2O_3, diamond, carbon nano tubes (CNT) etc. may also be compared in turning operation.

REFERENCES

[1] Vaz Jr, M. On the numerical simulation of machining processes. Journal of Brazilian Society of Mechanical Sciences **2000**, 22(2), 179-188.

[2] Klocke, F. and Eisenblatter, G. Dry cutting. *Annals of the CIRP* **1997**, 46(2), 519-526.

[3] Yildiz,Y. and Nalbant, M. A review of cryogenic cooling in machining processes. International Journal of Machine Tools & Manufacture **2008**, 48, 947–964.

[4] Sharma, V.S., Dogra, M. and Suri, N.M. Cooling techniques for improved productivity in turning. *International Journal of Machine Tools & Manufacture* 2009, 49, 435-453.

[6] He, J., Pei, H., Chu, Y., Wang, S. and Wang, G. MQL Application in high-speed turning bearing steel. *Applied Mechanics and Materials* **2014**, 490-491, 306-310.

[7] Hadad, M. and Sadeghi, B. Minimum quantity lubrication-MQL turning of AISI 4140 steel alloy. *Journal of Cleaner Production* **2013**, 54, 332-343.

[8] Dhar, N. R., Ahmed, M.T. and Islam, S. An experimental investigation on effect of minimum quantity lubrication in machining AISI 1040 steel. *International Journal of Machine Tools & Manufacture* **2007**,47, 748–753.

[9] Li, K. M. and Liang, S. Y. Performance profiling of minimum quantity lubrication in machining. *International Journal of Advanced Manufacturing Technology* **2007**, 35, 226–233.

[10] Kishawy, H.A., Dumitrescu, M., Ng, E. G. and Elbestawi, M.A. Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy. *International Journal of Machine Tools & Manufacture* **2005**, 45, 219–227.

[11] Sharma, J. and Sidhu, B.S. Investigation of effects of dry and near dry machining on AISI D2 steel using vegetable oil. *Journal of Cleaner Production* 2014, 66, 619-623.

[12] Khan, M. M. A., Mithu, M.A.H. and Dhar, N.R. Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. *Journal of Materials Processing Technology* **2009**, 209, 5573–5583.

[13] Dhar, N.R., Islam, M.W., Islam, S. and Mithu, M.A.H. The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. *Journal of Materials Processing Technology* **2006**, 171, 93–99.

[14] Attanasio, A. Gelfi, M., Giardini, C. and Remino, C. Minimal quantity lubrication in turning: Effect on tool wear. *Wear* **2006**, 260, 333–338.

[15] Wang, C.D., Chen, M., An, Q. L., Wang, M. and Zhu, Y. H. Tool wear performance in face milling inconel 182 using minimum quantity lubrication with different nozzle positions. *International Journal Of Precision Engineering And Manufacturing* **2014**, 15(3), 557-565.

[16] Aoyama, T. Development of a mixture supply system for machining with minimal quantity lubrication. *CIRP Annals - Manufacturing Technology* **2002**, 51(1), 289–292.

[17] Vasu, V. and Reddy, G.P.K. Effect of minimum quantity lubrication with Al2O3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. *Journal of Nanoengineering and Nanosystems* **2011**, 225(1), 3-16.

[18] Khandekar, S., Sankar, M. R., Agnihotri, V. and Ramkumar, J. Nano-cutting fluid for enhancement of metal cutting performance. *Materials and Manufacturing Processes* **2012**, 27, 963–967.

[19] Tawakoli, T., Hadad, M. J., Sadeghi, M. H., Daneshi, A. Stockert, S. and Rasifard, A. An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication—MQL grinding. *International Journal of Machine Tools & Manufacture* **2009**, 49, 924–932

[20] Tawakoli, T., Hadad, M. J. and Sadeghi, M. H. Influence of oil mist parameters on minimum quantity lubrication – MQL grinding process. *International Journal of Machine Tools & Manufacture* **2010**, 50, 521–531.

[21] Silva, L. R., Corrêa, E. C. S., Brandão, J. R. and Ávila, R. F. Environmentally friendly manufacturing: behavior analysis of minimum quantity of lubricant – MQL in grinding process. *Journal of Cleaner Production* **2013**, (Accepted manuscript).

[22] Silva, L. R., Bianchi, E. C., Catai, R. E., Fusse, R. Y., França, T. V., and Aguiar, P. R. Study on the behavior of the minimum quantity lubricant - MQL technique under different lubricating and cooling conditions when grinding ABNT 4340 steel. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* **2005**, *27*(2), 192-199.

[23] Suda, S., Yokota, H., Inasaki, I. and Wakabayashi, T. A Synthetic Ester as an Optimal Cutting Fluid for Minimal Quantity Lubrication Machining. *CIRP Annals - Manufacturing Technology* 2002, 51(1), 95-98.

[24] Hadad, M. J., Tawakoli, T., Sadeghi, M. H. and Sadeghi, B. Temperature and energy partition in minimum quantity lubrication-MQL grinding process. *International Journal of Machine Tools & Manufacture* 2012, 54–55, 10–17.

[25] Gopal, A. V. and Rao, P. V. Performance improvement of grinding of sic using graphite as a solid lubricant. *Materials and Manufacturing Processes* 2004, 19(2), 177-186.

[26] Singh, D. and Rao, P. V. Performance improvement of hard turning with solid lubricants. *International Journal of Advanced Manufacturing Technology* **2008**, 38, 529–535.

[27] Shen, B., Shih, A. J. and Tung, S. C. Application of nanofluids in minimum quantity lubrication grinding. *Tribology Transactions* **2008**, 51, 730-737.

[28] Malshe, A.P. and Verma, A (2006). Nanoparticle compositions and methods for making and using the same. International Application No. PCT/US07/60506.

[29] Shen, B., Malshe, A. P., Kalita, P. and Shih, A. J. Performance of novel MoS2 nanoparticles based grinding fluids in minimum quantity lubrication grinding. *Transactions of NAMRI/SME* 36 **2008**, 357-364.

[30] Shen, B. and Shih, A. J. Minimum quantity lubrication (MQL) grinding using vitrified CBN wheels. *Transactions of NAMRI/SME* **2009**, *37*, 129-136.

[31] Vamsi Krishna, P., Srikant, R. R. and Nageswara Rao, D. Experimental investigation on the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel. *International Journal of Machine Tools and Manufacture* **2010**, *50*(10), 911-916.

[32] Park, K. H., Kwon, P. Y. and Ewald, B. Effect of Nano-Enhanced Lubricant in Minimum Quantity Lubrication Balling Milling. *Journal of Tribology* **2011**, *133*(3), 0318031-8.

[33] Vasu, V. and Reddy, G. P. K. Effect of minimum quantity lubrication with Al_2O_3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. *Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanoengineering and Nanosystems* **2011**, *225*(1), 3-16.

[34] Nam, J. S., Lee, P. H. and Lee, S. W. Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication. *International Journal of Machine Tools and Manufacture* **2011**, *51*(7), 649-652.

[35] Khandekar, S., Sankar, M. R., Agnihotri, V. and Ramkumar, J. Nano-cutting fluid for enhancement of metal cutting performance. *Materials and Manufacturing Processes* **2012**, *27*(9), 963-967.

[36] Mao, C., Tang, X., Zou, H., Huang, X. and Zhou, Z. Investigation of grinding characteristic using nanofluid minimum quantity lubrication. *International Journal of Precision Engineering and Manufacturing* **2012**, *13*(10), 1745-1752.

[37] Setti, D., Ghosh, S. and Rao, P. V. Application of nano cutting fluid under minimum quantity lubrication (MQL) technique to improve grinding of Ti–6Al–4V Alloy. In *Proceedings of World Academy of Science, Engineering and Technology* (No. 70). World Academy of Science, Engineering and Technology **2012**.

[38] Kalita, P., Malshe, A. P., Arun Kumar, S., Yoganath, V. G., and Gurumurthy, T. Study of specific energy and friction coefficient in minimum quantity lubrication grinding using oil-based nanolubricants. *Journal of Manufacturing Processes* **2012**, *14*(2), 160-166.

[39] Lee, P. H., Nam, J. S., Li, C. and Lee, S. W. An experimental study on micro-grinding process with nanofluid minimum quantity lubrication (MQL). *International Journal of Precision Engineering and Manufacturing* **2012**, *13*(3), 331-338.

[40] Mao, C., Zou, H., Huang, X., Zhang, J. and Zhou, Z. The influence of spraying parameters on grinding performance for nanofluid minimum quantity lubrication. *The International Journal of Advanced Manufacturing Technology* **2013**, *64*(9-12), 1791-1799.

[41] Roy, S. and Ghosh, A. (2014). High-speed turning of AISI 4140 steel by multi-layered TiN top-coated insert with minimum quantity lubrication technology and assessment of near tool-tip temperature using infrared thermography. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 0954405413514570.

[42] Khalilpourazary, S. and Meshkat, S. S. Investigation of the effects of alumina nanoparticles on spur gear surface roughness and hob tool wear in hobbing process. *The International Journal of Advanced Manufacturing Technology* **2014**, 1-12.

[43] Sayuti, M., Erh, O. M., Sarhan, A. A. and Hamdi, M. Investigation on the morphology of the machined surface in end milling of aerospace AL6061-T6 for novel uses of SiO_2 nanolubrication system. *Journal of Cleaner Production* **2014**, 66, 655-663.

[44] Rahmati, B., Sarhan, A. A. and Sayuti, M. Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS_2) nanolubrication in end milling machining. *Journal of Cleaner Production* **2014**, 66, 685-691.

[45] Rahmati, B., Sarhan, A. A. and Sayuti, M. Investigating the optimum molybdenum disulfide (MoS_2) nanolubrication parameters in CNC milling of AL6061-T6 alloy. *The International Journal of Advanced Manufacturing Technology* **2014**, *70*(5-8), 1143-1155.

[46] Mao, C., Zou, H., Zhou, X., Huang, Y., Gan, H. and Zhou, Z. Analysis of suspension stability for nanofluid applied in minimum quantity lubricant grinding. *The International Journal of Advanced Manufacturing Technology* **2014**, 71, 2073–2081.

[47] Amrita, M., Srikant, R. R. and Sitaramaraju, A. V. Performance evaluation of nanographite-based cutting fluid in machining process. *Materials and Manufacturing Processes* **2014**, *29*(5), 600-605.

[48] Saravanakumar, N., Prabu, L., Karthik, M. and Rajamanickam, A. Experimental analysis on cutting fluid dispersed with silver nano particles. *Journal of Mechanical Science and Technology* **2014**, *28*(2), 645-651.

[49] Sayuti, M., Sarhan, A. A. and Salem, F. Novel uses of SiO_2 nano-lubrication system in hard turning process of hardened steel AISI4140 for less tool wear, surface roughness and oil consumption. *Journal of Cleaner Production **2014***, 67, 265-276.

[50] Mao, C., Huang, Y., Zhou, X., Gan, H., Zhang, J. and Zhou, Z. The tribological properties of nanofluid used in minimum quantity lubrication grinding. *The International Journal of Advanced Manufacturing Technology* **2014**, 1221-1228.